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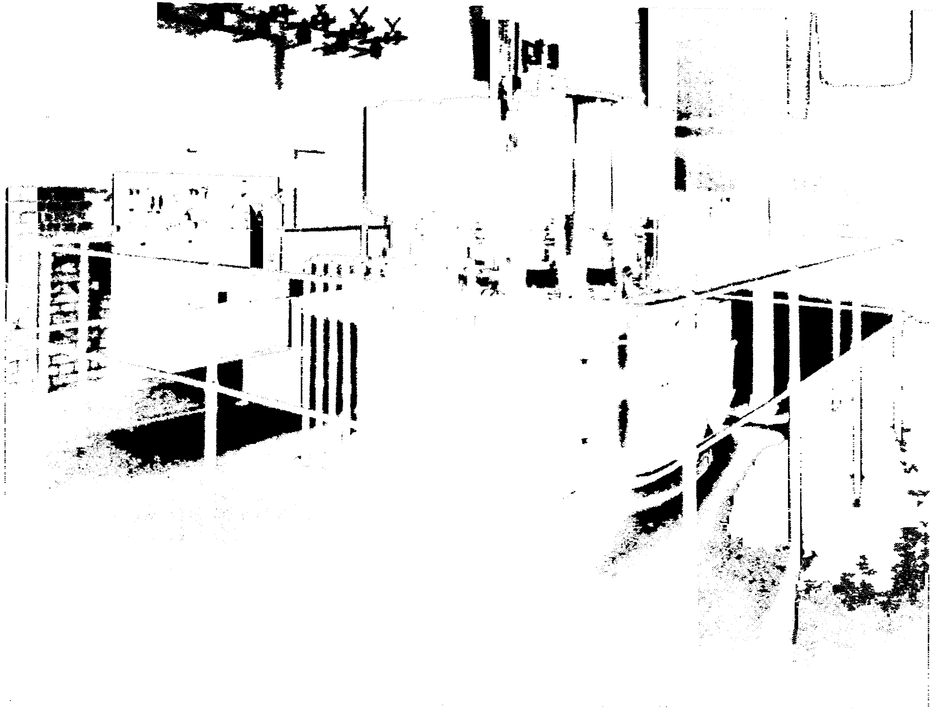

THE FIRST ALL-BRITISH STEEL TANK RECTIFIER UNIT

(See Page 7)

British Thomson Houston Co., Ltd

MERCURY-ARC CURRENT CONVERTORS

AN INTRODUCTION TO THE THEORY AND PRACTICE OF VAPOUR-ARC DISCHARGE DEVICES AND TO THE STUDY OF RECTIFICATION PHENOMENA

BY

H. RISSIK, HONS. B.SC. (ENG.)

WITH A FOREWORD BY

CAPTAIN J. M. DONALDSON

M.INST.C.E., M.I.E.E.

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FOREWORD

Some thirty or forty years ago there was raging in London what used to be called the "Battle of the Systems" between the advocates of continuous current on the one hand and of alternating current on the other.

In the early days, the fortunes of the battle inclined to the continuous-current side, whose protagonist was Col. Crompton, mainly because the legislation of those days practically enforced small distribution areas, while the secondary battery was an enormous help in maintaining supply. Ferranti, however, pointed out that the centre of a distribution area was by no means the right place for a generating station, and showed at Deptford that much better results could be obtained by placing the power station where cooling water was readily come by and the obtaining of coal was cheap and convenient; and that, when current had to be transmitted at a distance, alternating current transmission and generation was undoubtedly indicated.

It was probably the advent of the steam turbine which gave the *coup de grâce* to the advocates of continuous current inasmuch as the continuous-current generators driven by turbines were never very practical and were exceedingly difficult and expensive to construct. So then it followed that, as for the larger generators turbine-driven alternators had perforce to be used, generation and also transmission definitely became the province of alternating current.

This, then, left continuous-current distribution in a difficult position inasmuch as to convert to continuous current the alternating current which had been generated it was necessary to employ rotating machinery, which was not only much more expensive than static transformers but occupied considerably more room and involved expensive attendance. This difficulty was partially solved by ingenious systems of remote control which, in themselves, were very expensive and could be applied with economy only to larger units, so that the advantages still remained with alternating-current distribution.

There were, however, difficulties in converting a three-wire continuous-current system to the standard three-phase system, and this was commonly met in residential areas by the use of special six-phase transformers. This, however, involved the separation of the network into three distinct portions which could not be inter-connected, and was not always very convenient to carry out in such cases where it was not considered advisable to run an entirely three-phase four-wire network.

However, many such conversions were successfully made —and then, curiously enough, the pendulum swung another way owing to a new development, viz. Wireless Broadcasting. Whereas in the old days when changing over a continuous-current network to alternating-current working one had, in a residential area, merely to deal with a few articles of domestic use with, possibly, an occasional difficult dentist's or surgeon's installation, now one finds that nearly every consumer has a wireless set which requires conversion—sometimes a very expensive matter indeed, but in all cases involving quite a considerable sum. There is no doubt at all that this situation has caused the change over of continuous-current systems to slow down and, in recent years, the situation has been very largely changed by the advent of the mercury rectifier, which is the subject of the present book.

The rectifier has proved a most potent weapon in the hands of the distribution engineer inasmuch as he is now in a position to convert from alternating to continuous current with much higher efficiency than was the case with rotating machines, with a small requirement of space, and without the necessity for attendance. This applies not only to distribution systems but also to traction systems, and it has become a very simple matter to supply continuous current to a railway or tramway system and to control all the converting plant centrally from a single point, as, indeed, has been done in the case of the Southern Railway system at Three Bridges. Although the glass-bulb mercury-arc rectifier has been on the market for many years, it is only recently that it has been developed on a scale which makes possible its use in large units, and the development has been so rapid that there is, as far as I know, no single book which gives a complete and up-to-date survey of the developments of this very useful piece of apparatus and of its theory, operation, and peculiarities. This book by Mr. Rissik, therefore, should fill a void in technical literature, and it has the advantage that it is completely up to date.

Moreover, there are certain less known developments of the convertor which are dealt with fully in this book, such, for instance, as the invertor and the cyclo-convertor which are dealt with in Chapters XI and XII. The first of these makes it possible to deal with long-distance transmission by using continuous instead of alternating current at high pressure, and getting a great many of the advantages which are associated with alternating-current distribution. The very ingenious system of Dr. Thury enabled one to do this same thing, but its scope was very limited, and the complications were considerable, and were overcome only by an extraordinary amount of ingenuity. With the invertor, however, the problem becomes much simpler and more easy to handle, and, although the development in this direction has so far not been notable, the possibilities are great.

It is, therefore, incumbent on everybody who is interested in these matters to study carefully the possibilities which are opened up by this apparatus. And I venture to commend this book to the notice of Engineers and Students as a comprehensive account of a piece of apparatus which will become increasingly useful as time goes on.

J. M. DONALDSON

NORTHMET HOUSE.
May, 1935.

PREFACE

THE development that has taken place in mercury-arc rectifier technique since the first edition appeared in 1935 has tended mainly toward the perfecting of the rectifier and its auxiliaries, and toward the elimination of those factors productive, possibly, of unreliability in service. The most notable advance in this direction is represented by the so-called "steel-bulb" or pumpless air-cooled steel-clad rectifier, and Chapters VII and XVI have been extended to include an account of this new development, at least as far as British practice is concerned.

Progress on the Continent during this same period seems to have lain chiefly in the direction of perfecting some of the newer applications of the grid-controlled rectifier, e.g. the use of rectifier-invertor combinations for reversing d.c. drives (rolling mills and colliery winders) and of cycloconvertor systems in a.c. traction supply. In the United States of America, on the other hand, the advance in rectifier technique has been directed to applying mercury-arc discharge devices to the solution of problems connected with electrical machines, and has led *inter alia* to the development of the so-called "thyratron commutator motor" and of new super-excitation systems for a.c. generators. All these developments are, however, still in a state of flux so that no useful purpose is to be served by including their description in the present edition.

The author has taken the opportunity afforded by the appearance of a second edition of correcting a number of errors, typographical and otherwise, and of adding one or two references to developments that have taken place since the first edition was published.

H. RISSIK

KENSINGTON.
July, 1940.

PREFACE TO THE FIRST EDITION

No apology is needed in introducing the present work, which has been written primarily for the electrical student. Although there is available a vast amount of literature dealing with the rectification of alternating currents by means of vapour-arc discharge devices, the bulk of this is not readily accessible, being scattered throughout numerous foreign technical journals. At the same time the author is unaware of any single collection of such material that might usefully form a basis for study in the electrical engineering classes of our universities, technical colleges and evening schools. The same remark applies, but perhaps in lesser degree, to the few standard works of reference on this all-important subject which have so far made their appearance.

The classic treatise by Marti and Winograd (1930)* is a book intended rather for the designer and the advanced engineer, although its later chapters, being devoted to a description of steel-tank rectifiers and their operating features, are valuable to the student in so far as they illustrate current American practice in the application of the mercury-arc rectifier. Again, the monumental work by Müller-Lübeck (1929)† is throughout so rigorously mathematical in treatment that it can be regarded only as meat for the professors. This is particularly true of its first volume, notwithstanding that it constitutes what is undoubtedly the most searching and exhaustive exposition of the rectifier theory. On the other hand, the earlier part of its second volume contains much that is really useful to the advanced student; whilst, in the same way, the later part affords a valuable insight into continental practice in the use of both glass-bulb and steel-tank rectifiers. A shorter and somewhat earlier book by Prince and Vogdes (1926)‡ has recently been enlarged, revised, and brought up to date by Gramisch for the German edition (1931).§ This little treatise represents what is probably the best introduction to the study of the mercury-arc rectifier, alike in its physical and its electrical aspects, which has as yet been published.

---

* *Mercury-arc Power Rectifiers* (McGraw-Hill Book Co., New York).

† *Der Quecksilberdampf-Gleichrichter* (Julius Springer, Berlin).

‡ *Principles of Mercury-arc Rectifiers and their Circuits* (McGraw-Hill Book Co., New York).

§ *Quecksilberdampf-Gleichrichter* (R. Oldenbourg, Munich).

None of these works of reference, however, deals with rectifier theory in an elementary manner calculated to meet the needs of the student mentally confronted with this new converting apparatus for the first time, and preparing, if somewhat reluctantly, to grapple with the entirely fresh set of problems that its operation involves. The reason for this must be sought in the fact that the fundamentals of arc rectification are so far divorced from electrodynamics that the orthodox methods of analysing and presenting electrical circuit phenomena, and which are commonly applied to the study of electrical machines, can find no parallel in the study of the mercury-arc rectifier.

The methods adopted in the above standard works of reference, and which, moreover, have been universally employed in rectifier literature up to the present, are based on the rigorous analysis of the rectifier problem established originally by Dällenbach and Gerecke in their classic paper, "The Current and Voltage Relations of the Mercury-arc Rectifier," published in 1924.* Unfortunately this analysis admits of none of the simplicity of treatment associated with conventional vector and circle diagrams. The theory of arc rectification has consequently remained a closed book except to the rectifier expert and, possibly, to the inquiring engineer with a flair for mathematics.

Realizing the need for a more simple and generally acceptable treatment of the rectifier problem, the author some years ago developed a method of diagrammatic presentation and analysis which he has since found of considerable assistance in explaining the electrical principles involved in arc rectification and in evaluating the various rectifier circuit data. The present book has been inspired by memories of student days, still sufficiently vivid for the author to be able to appreciate the mental efforts inseparable from the complete understanding of new concepts. And it has been written in the hope that it may help materially in removing the veil of mystery which apparently surrounds the vapour-arc discharge device, as well in its practical applications as in the theory of its operation; and that, in so doing, it may succeed in laying bare to the student an apparatus which bids fair to revolutionize our electrical engineering practice in many important respects.

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* *Archiv für Elektrotechnik*, Vol. 14, pp. 171–246.

After a short introductory chapter dealing with the historical evolution of the mercury-arc rectifier and a chapter on the physical principles underlying its operation, a considerable portion of the book is devoted to rectifier circuit theory, use being made of this new method of treatment in calculating the vital transformer data. A liberally illustrated chapter on modern practice in the construction of both glass-bulb and steel-tank rectifier equipments completes the first part of the book.

Subsequent chapters deal with the physics of grid-controlled vapour-arc discharge devices, with the theoretical principles involved in grid control, and with the several applications of grid-controlled rectifiers and mercury-vapour valves. Final chapters are devoted to the generation of harmonics by the mercury-arc rectifier and the bearing this has on the power-factor problem, and to the calculation of the principal design data in the case of two typical rectifier installations. The book concludes with a chapter descriptive of the latest British practice in the design and equipment of static convertor sub-stations, as exemplified by several recent installations of rectifier plant in this country. Although the bulk of the text is taken from earlier papers and articles by the author, certain material has been derived from papers which have appeared in various technical journals during the last few years. In each case due acknowledgment is given in the form of a short bibliography at the end of the chapter concerned.

A word or two about labels. Exception may be taken to the title "Mercury-arc Current Convertors," and this perhaps requires some elucidation. In view of certain shortcomings in the terminology appropriate to arc rectifiers and kindred discharge devices, the author has found it expedient in places to borrow from the German, a language singularly rich in pithy terms and descriptive phraseology, especially where technical writing is concerned. The terminology first suggested by Dr. Wechmann has accordingly been adopted throughout the book. A "current convertor" (*stromrichter*) is thus a device for converting alternating to direct current or *vice versa*, or for converting alternating current of one frequency into alternating current of another frequency. This general term then includes the more specific terms: "rectifier" (*gleichrichter*), "invertor" (*wechselrichter*), and "cycloconvertor" (*umrichter*).

Care has been taken in selecting the illustrations for the book to ensure that British practice is predominantly represented; and it is hoped that the photographs and descriptions of such rectifier plant contained in Chapters VII and XVI will enable the reader to gain a general idea of our modern rectifier technique. It should be remembered in this connection that, with one notable exception, the development of the all-British rectifier began less than five years ago. For all information of this kind the author is indebted to the several rectifier manufacturers in Great Britain; in particular to the British Thomson-Houston Co., Messrs. Bruce Peebles & Co., the English Electric Co., the General Electric Co., and the Hewittic Electric Co.

H. RISSIK

EDGBASTON.
February, 1935.

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MERCURY-ARC CURRENT CONVERTORS

PART I—RECTIFICATION

CHAPTER I

THE EVOLUTION OF THE MERCURY-ARC RECTIFIER

Early Developments. The mercury-arc rectifier in its present form is the direct outcome of the invention of the mercury-vapour lamp towards the end of the nineteenth century, whilst the rather unusual design which characterizes this type of electrical apparatus is a natural consequence of the development it has undergone since the rectifying properties of these early vapour lamps were first observed.

The physical principles underlying the behaviour of the mercury-arc rectifier would seem to have been recognized in the first place by Jemin and Meneuvrier, who, in 1882, gave an account of the property of an electric arc established between mercury and carbon electrodes, by which the current would flow in one direction only. Some time later, in 1889, and a year or two before Arons constructed his first mercury-vapour lamp, Fleming made a general investigation of the unilateral conductivity of the electric arc in air. Later still, in 1894 and 1898, Sahulka described the results of similar investigations with respect to atmospheric arcs established between mercury and iron or carbon electrodes.

In the course of all these early experiments, however, no thought was as yet being given to questions of practical application. A prerequisite to any development in this direction was the enclosure of the mercury arc in an evacuated vessel, exemplified by Arons's mercury-vapour lamps (1890–1892). In this way only could anything like a reasonable efficiency be obtained with apparatus of this nature. But it was not until Cooper-Hewitt took up the manufacture of mercury-vapour lamps on a commercial scale that a rectifier, operating on the unidirectional principle of the mercury arc, began to emerge as the nineteenth century drew to a close. It is noteworthy that he not only evolved the basic forms of the rectifier bulb in the case of the glass type of mercury-arc rectifier, but that, in addition, he established the lines along which the steel-tank rectifier was later to develop. And what seems more remarkable still, considering that electro-physics was at that time yet in its infancy, is the fact that Cooper-Hewitt even indicated the possibility of controlling the arc by means of a third electrode, or grid, situated in the discharge path between anode and cathode; and that, in so doing, he foreshadowed the application of grid-control to achieve voltage regulation of the rectifier.

The Glass-bulb Rectifier. In the initial stages of its evolution from the mercury-vapour lamp, the glass rectifier was successfully manufactured in small sizes only, and thus had a very limited application, in spite of its great advantage—that its functioning is inherently static. The limiting feature in the design of these early glass-bulb rectifiers was the means of conducting the current to the anodes and cathode in a durable and air-tight manner. As time passed, however, and more experience was gained in the construction of these rectifiers, rapid strides were made as well in the development of metal-to-glass vacuum seals as in the manufacture of a glass which could withstand the extreme temperature differences associated with commercial apparatus embodying this new system of rectification. As the result, glass-bulb rectifiers capable of carrying 100 amperes and more were constructed by several manufacturers in the years immediately preceding the Great War. But an entirely fresh difficulty was encountered when the endeavour was made still further to increase the current output from individual rectifier bulbs and especially when, at the same time, it was attempted to attain higher output voltages. It was found that under more extreme conditions of load and/or voltage a sudden failure of the valve action would take place at one or more of the rectifier anodes, a phenomenon generally referred to as "backfiring" or "arcing back." Although it was soon recognized that the general reason for this peculiar failure of the unidirectional property of the mercury arc between electrodes *in vacuo* was of a physical nature, the origin of the phenomenon itself remained obscure until the researches of Langmuir, Güntherschulze, and, more recently, of von Issendorff established that its occurrence is a function primarily of the vapour-pressure in the rectifier and the operating voltage, and that it also depends on the presence of impurities in the anode and cathode materials as well as of foreign gases in the rectifier bulb. In modern glass-bulb rectifiers the two latter factors have become relatively unimportant by reason of the use of chemically pure mercury and electro-graphite, and of the perfecting of means for baking-out the rectifier during the final stages of evacuation. Nowadays, therefore, the question of increased output is almost entirely one of efficient cooling of the rectifier bulb and also, of course, of glass-blowing technique. It would appear that the limiting output for a reliable glass-bulb rectifier is at present in the neighbourhood of 500 amperes direct current at pressures not exceeding about 500 or 600 volts.

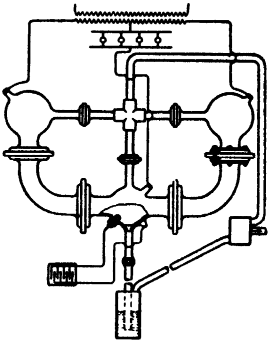

FIG. 1. THE FIRST DESIGN PUT FORWARD FOR A METAL-CLAD MERCURY-ARC RECTIFIER (COOPER-HEWITT, 1908)

The Steel-tank Rectifier. It is because of this limitation inherent in the glass-bulb design that the steel-tank type of mercury-arc rectifier has perforce been developed for current outputs above 500 to 750 amperes, when it commences to be an economical proposition. But it must not be thought, therefore, that the advent of the steel-tank rectifier is of comparatively recent date only. On the contrary, soon after the first few commercial rectifiers of the glass type made their appearance the desire arose to replace the glass bulbs, brittle and limited in output as these were, by a more robust form of rectifier vessel such as a metal container for example. As already mentioned, Cooper-Hewitt was among the first to take up the general problem of designing a metal-clad rectifier; and Fig. 1, taken from a patent* specification which appeared as early as 1908, illustrates his first attempt at reaching a solution. This particular design is noteworthy in that it recognized the fact that an electric arc established between insulated electrodes, and in an atmosphere of mercury vapour at low pressure, is unimpeded by any metal surfaces surrounding it—a principle which holds good to this day. The arrangement illustrated in Fig. 1* consisted mainly of a system of pipes into which the anodes and cathodes were inserted through ground porcelain sealing joints having conical surfaces.

---

* Amer. Pat. No. 1,007,694, granted in 1911.

The construction of water-cooled, metal-clad rectifiers on the lines laid down by Cooper-Hewitt was first undertaken in America by the General Electric and Westinghouse Companies, and Fig. 2* depicts a steel-tank rectifier built by the latter firm in 1910. The strong influence exercised upon these early designs by the glass-bulb type of rectifier, which was by then well established, is evident from this illustration. In Europe, Bela Schäfer was working along somewhat similar lines at the same time, but independently of these American developments, until in 1910 he introduced a successful design† of metal-clad rectifier which broke away from the hitherto accepted practice of construction and was the forerunner of the modern steel-tank type of mercury-arc rectifier. He appears to have been the first to recognize that the special dome of large surface area for condensing the mercury vapour which, due to the poor heat conductivity of glass, is an essential feature of the glass-bulb rectifier, could be dispensed with where the rectifier vessel is of metal throughout; and that the anodes need therefore no longer be confined in special arms protruding from the base of the condensing chamber, but might be arranged inside the rectifier vessel proper. Subsequent development of this

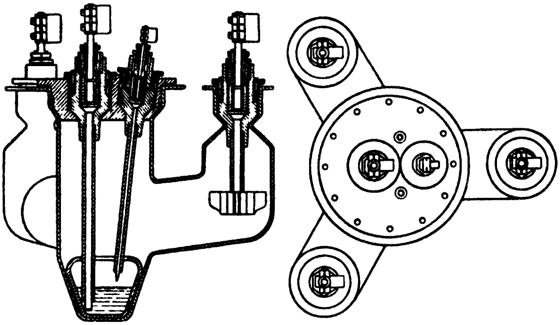

FIG. 2. EARLY DESIGN FOR STEEL-TANK RECTIFIER (WESTINGHOUSE ELECTRIC CO. 1910)

design of steel-tank rectifier on a commercial scale was undertaken by Brown-Boveri et Cie, who, in 1911, supplied what may be considered as the first complete converting installation incorporating a rectifier of this type. Shortly afterwards, in 1912, the Allgemeine Elektrizitäts-Gesellschaft took up the production of steel-tank rectifiers on the basis of the American design already established by the General Electric Co., and which, incidentally, allowed of units having outputs of 600 to 700 amperes direct current at 1 200 and even 2 400 volts being built successfully as early as 1913. Soon after the Great War, however, the A.E.G. abandoned this method of construction in favour of that introduced by Krämer, which has remained practically unchanged to this day. The new design, illustrated

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* The illustrations Figs. 1 and 2 have been taken from K. E. Müller-Lübeck's *Quecksilberdampf-Gleichrichter*, published by Messrs. Julius Springer, to whom the author is indebted for permission to reproduce them.

† *Vide E.T.Z.*, 1911, Vol. 32, p. 2.

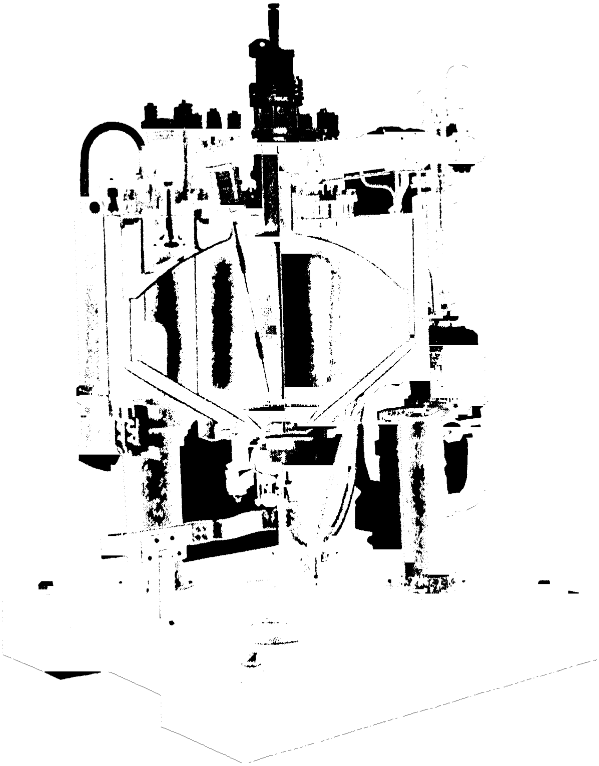

FIG. 3. A MODERN DESIGN OF STEEL-TANK RECTIFIER
A.E.G. Co.

in Fig. 3, consisted in the main of two conical vessels welded together at an horizontal joint and completely enclosed by a cooling-water tank through the cover of which the anode arms projected, the latter being welded into the upper vessel. A modified form of this design is now followed by the General Electric Co. in America.

During the War years, the Siemens-Schuckert-Werke also commenced the manufacture of steel-tank rectifiers, but on quite independent lines. The successful design which was eventually adopted by this concern, and for whose development Schenkel was primarily responsible, represented a radical departure from the hitherto accepted practice in steel-tank rectifier construction in that a special water-cooling system was provided inside the arc chamber or rectifier vessel proper (Fig. 4). In the course of time other continental firms, realizing the many advantages of static over rotating converting plant for heavy-duty service, began to interest themselves in the manufacture of steel-tank rectifiers. So that in recent years several electrical manufacturers, other than the three leading makers already mentioned, have also been producing steel-tank rectifiers on the Continent: notably, A.S.E.A. in Sweden, Bergmann in Germany, A.C.E.C. in France, and C.K.D. in Czechoslovakia.

Compared with the rapid progress made on the Continent in the application of mercury-arc rectifiers, at any rate as regards those of the steel-tank type, development in Great Britain has been relatively slow. This is to be attributed not so much to any innate conservatism on the part of British engineers, but rather to the fact that the rotary convertor has reached a higher standard of perfection in this country than on the Continent. It is also to be remembered that the reputation of the steel-tank rectifier suffered in consequence of the rather reckless claims that were advanced for it on its being first introduced into this country, claims which, moreover, were not substantiated later. So that British manufacturers of rotary convertors, who quite naturally would not view with equanimity a competitive introduction of continental steel-tank rectifiers, were enabled with good reason to discredit the new converting plant in the eyes of prospective customers. However, the prejudice thus formed against the rectifier by engineering opinion in this country has by now been lived down, and during the last few years several British firms have taken up its commercial production. The first of these to manufacture a successful steel-tank rectifier was the British Thomson-Houston Co., who, at the end of 1930, supplied a 1 500-kW 615-volt unit to the London Underground Railways

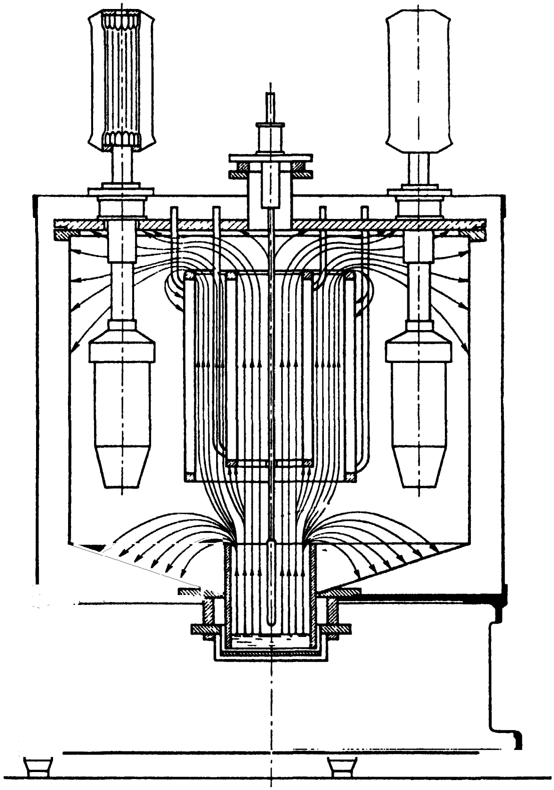

FIG. 4. ANOTHER RECENT DESIGN OF STEEL-TANK RECTIFIER
Siemens-Schuckert-Werke

—the first all-British steel-tank rectifier to be put into commercial service, *vide* Frontispiece. During 1931 both the General Electric Co. and Bruce-Peebles & Co. commenced the regular production of steel-tank rectifiers, followed by the English Electric Co. early in 1932.

Grid Control of the Mercury-arc Rectifier. The possibility of controlling the current arc in a mercury-vapour rectifier by means of grids, situated in the discharge path between the anodes and the cathode, had already been recognized by Cooper-Hewitt, and as early as 1903 he even indicated the possibility of applying potential impulses to these grids in such a manner that the instant at which the arc discharge took place could be altered as desired. Later, in 1914, Langmuir showed how to control the time of starting of the current arc in a *thyratron* tube* in such a way that the average value of the current through the valve could be varied at will, using a steady grid potential of variable magnitude. A much improved method of control was put forward by Toulon, in 1924, who employed an alternating grid potential of the same frequency as the anode voltage, but variable in phase. This system of grid control is probably the most commonly employed at the present time. An alternative method of control having the same effect was developed by Mittag in 1925, and made use of an alternating grid potential superimposed upon a steady bias potential, the latter being variable in magnitude and its value being either positive or negative (with respect to the cathode) as required.

However, the first practical mercury-arc rectifier incorporating control grids appears to have been developed by Langmuir and Prince in 1928.† This was a small unit of the glass-bulb type. The application of grid control to steel-tank rectifiers was undertaken shortly afterwards by Brown-Boveri et Cie., and by both the Siemens-Schuckert-Werke and the A.E.G. at about the same time. On the occasion of the Second World Power Conference, held in Berlin in the summer of 1930, all three firms took the opportunity of staging in their works and laboratories comprehensive displays illustrative of this most recent development in rectifier technique. A review of these expositions appeared in several of the leading technical journals on the Continent towards the end of 1930.

The first general account of the grid-controlled rectifier to be given in the British technical Press was contained in an article by the author dealing with recent developments in the application of mercury-arc rectifiers to heavy-duty work, and published in the *Electrical Review*‡ some four years ago. From about this time onwards, rectifier manufacturers in Great Britain began seriously to consider the possibilities opened up by grid control, although it would seem that the English Electric Co. were largely responsible for the pioneer work in the direction of its general application to the mercury-arc rectifier in this country. In fact, it was not until this firm held an exhibition in its principal works towards the end of 1932, of which the leading feature was a demonstration of the possible applications of grid-controlled rectifiers, and of which details were published in the technical Press at the time, that British engineering circles became fully aware of a development that has already considerably widened the scope of static converting plant and which, moreover, contains the elements of a revolution in electrical engineering practice.

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* A three-electrode valve operating with mercury vapour and employing either a directly or indirectly heated solid cathode.

† Vide *General Electric Review*, 1928, Vol. 31, p. 347; and 1929, Vol. 32, p. 213.

‡ *Electrical Review*, 1931, Vol. 108, p. 991.

As the result of this awakened interest and the subsequent demand which it has created for rectifier equipment for all kinds of service, rectification technique in this country has forged ahead rapidly during the last three years. To-day the British mercury-arc rectifier is fully the equal, if in some respects not actually the superior, of the continental product.

CHAPTER II

THE PHYSICAL PRINCIPLES UNDERLYING ARC RECTIFICATION

Fundamental Principles. The function of a rectifier is to transmute electrical energy from the alternating-current to the direct-current form. In the mercury-arc rectifier this transmutation of energy takes place as a direct process, because such apparatus is, in the last analysis, simply a switching device, the moving element being represented by a current arc *in vacuo.*

Mercury-arc rectifier equipment thus differs fundamentally from rotating converting plant, in which the change in form of the electrical energy is accomplished by a process of conversion involving the transfer of power either mechanically or by electro-dynamic action, or by both means, from the alternating-current side to the direct-current side of the apparatus. This fundamental distinction in principle between the mercury-arc rectifier and the rotating convertor or, in other words, between the processes of rectification and conversion, is frequently overlooked when considering the practical applications of both types of plant. But it is important because it leads, for example, to the rating of such rectifying apparatus being based almost entirely on its current-carrying capacity alone, largely irrespective of the operating voltage; that is to say, the power output of a given size of rectifier unit is, within limits, proportional to the output voltage.

Reference has already been made in the previous chapter to the investigations conducted by Fleming in 1889 as the result of a phenomenon observed some years previously in connection with the carbon filament lamp, and known after its discoverer as the "Edison effect." During the course of these investigations he established the unilateral conductivity of the electric arc, and his experiment to demonstrate this phenomenon is illustrated by Fig. 5.* An arc maintained between two ordinary carbon electrodes was deflected by means of a magnet so as to come into contact with a third electrode, also of carbon. On connecting a battery and galvanometer between the negative carbon and this third electrode, it was found that the galvanometer was deflected only when the negative carbon was in connection with the negative pole of the battery. No deflection was observed when the negative carbon was connected to the positive pole. This experiment went to show that the electric arc would allow current to pass in one direction only. And, as Fleming himself expressed it at the time—

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* This illustration has been kindly furnished by Sir Ambrose Fleming, and is taken from his paper on "Problems in the Physics of the Electric Lamp," read before the Royal Institution of Great Britain on 14th February, 1890.

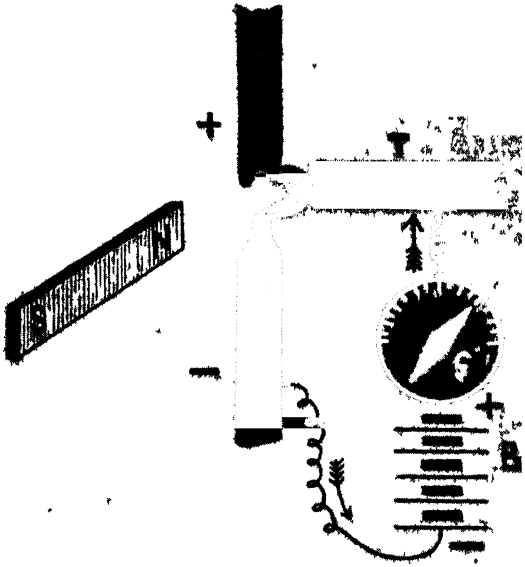

FIG. 5. FLEMING'S EXPERIMENT DEMONSTRATING THE UNILATERAL CONDUCTIVITY OF THE ELECTRIC ARC

> Negative electricity can pass along the flame-like projection of the arc from the hot negative carbon to the cooler third carbon, but not in the opposite direction.

In modern parlance, the above phenomenon illustrates the principle that electrons emitted from a cathode are attracted towards an anode at suitable potential, thereby permitting current to flow between them. When the cathode and anode are placed in a vacuum the electron emission is greatly enhanced, much as if the extraction of the air largely removed resistance to the motion of the electrons. At the same time the state of vacuum necessitates a large potential difference between anode and cathode to drive the electrons across the intervening space, because the accumulation of electrons there produces a negative space-charge which tends to impede the emission of further electrons from the cathode. The presence of a rarefied gas which is readily ionized assists in neutralizing this space-charge, thereby reducing the potential difference required to cause current to flow between anode and cathode. In this respect, mercury vapour has the advantage that the necessary potential difference is only some 20 to 30 volts.

The most important advantage arising from the use of mercury as a cathode is that it is liquid at ordinary temperatures. In the majority of vacuum rectifiers, employing a solid cathode heated to incandescence by external means, the material is permanently removed from the cathode surface, ultimately destroying its utility, and accumulates in an ever-increasing layer on the walls of the vacuum chamber. In the mercury-arc rectifier, on the other hand, the incandescent portion of the cathode is continually replenished, and the initial charge of mercury lasts indefinitely. The heat generated by the passage of the rectifier current through the mercury surface causes a stream of mercury vapour to be projected upwards into the vacuum chamber, where it is condensed by appropriate cooling arrangements and led back to the cathode. The mercury-arc rectifier thus consists principally of an air-tight chamber, under vacuum, containing one or more solid anodes situated above a cathode of liquid mercury; whilst the basis of its operation is simply that characteristic of the electric arc which permits current to flow in one direction only, namely, from anode to cathode.

Electron Theory. The physical behaviour of the mercury-arc rectifier, which has only become fully understood in comparatively recent times, is closely allied to that of the vacuum rectifier or *diode*; so that any explanation, however brief or elementary, of the physics of arc rectification can only commence with a general account of the electron discharge and the reasons underlying its valve action.

According to the present theory, the atom—the smallest known particle of matter—consists of a positively charged core or nucleus around which revolve one or more negatively-charged particles, called *electrons*. The electrons are held in their orbits by the positive charge of the nucleus, the force of attraction and the number of electrons varying with the different elements. At a high temperature, or under the influence of an electric field, the force of attraction between the electrons and the positive nucleus around which they revolve can be overcome, and the electrons liberated. The facility with which an electron may be dislodged from its orbit and thus dissociated from the atom depends on several factors—pressure, temperature, the strength of the electric field, and the structure of the atom. An atom from which an electron has been removed carries an excess of positive charge and is termed a *positive ion.* Similarly, an atom which has acquired an extra electron carries an excess of negative charge and is called a *negative ion.* The process by which electrons are dissociated from atoms is known as *ionization*, and the atoms are said to be *ionized.* If an electron, while moving at high speed under the influence of an electric field (such as that existing between two electrodes at opposite potentials), collides with a neutral atom or molecule of gas or vapour, it may liberate an electron by the impact of the collision. This phenomenon is known as *ionization by collision.*

The atom from which an electron has been thus liberated becomes, as the result, a positive ion, and consequently moves in a direction opposed to that of the electron flow. Electrons, being negatively charged particles, travel from a negative electrode, or *cathode*, towards a positive electrode, or *anode*; hence positive ions travel from anode to cathode. The combined movement of electrons and positive ions constitutes a flow of electric current between the electrodes. In accordance with convention, we consider the direction of flow to be from anode to cathode, as if the current were carried solely by the positive ions. In actual fact, however, practically the entire current in a mercury-arc rectifier is carried by the electrons streaming from cathode to anode. This is accounted for by the fact that the electrons travel at a very much higher speed than the ions, due, in turn, to the fact that the mass of an electron is very much smaller than that of a positive ion, the ratio being approximately 1 to 400 000 in the case of mercury.

The Electron Discharge. Of the several ways in which a negative electrode, or cathode, may be made to emit electrons, the most important from the point of view of rectification consists in raising its temperature to a sufficiently high value. This phenomenon is known as *thermionic emission.* If the cathode consists of a material in which the electrons are loosely bound to the nuclei, the electrons are more readily dissociated; whilst if the cathode is placed in a vessel evacuated to a high degree, the electrons can travel without encountering much resistance and their emission is thus greatly enhanced.

In the vacuum valve (*diode*), or *thermionic rectifier*—to give it the name by which it is more generally known—a cold electrode, the anode, is placed in proximity to the heated cathode. If an alternating voltage be applied between the two, then electrons will travel across the intervening space only during that half of the voltage cycle in which the anode potential is positive with respect to the cathode. This period is called the *conducting* or *permeable half-cycle* of anode voltage. During that half of the voltage cycle in which the anode potential is negative with respect to the cathode, the electrons are repelled, and are prevented from reaching the anode. This period is correspondingly referred to as the *non-conducting* or *impermeable half-cycle* of anode voltage. It is this unidirectional property of the electron discharge which has caused the name of "valve" to be applied to such rectifying apparatus.

The Arc Discharge. With arc rectifiers, in which the current is carried not by electrons alone, but by positive ions as well, the emission of electrons is characterized by what is known as the *cathode spot*—an incandescent spot on the surface of the cathode at which particles of the cathode material are vaporized and are ejected with a very high velocity. In the case of the mercury-arc rectifier, the velocity of the mercury-vapour stream emanating from the cathode is of the order of 20 000 cm. per second, or about 450 miles per hour. There is some uncertainty as to the temperature of the cathode spot itself. It is probably in the neighbourhood of 600° C., the current density being about 4 000 A per sq. cm., or 25 000 A per sq. in. The brilliancy of this spot appears to be due to a luminous curtain or cloud of incandescent mercury vapour close to and immediately above it, and having a temperature of approximately 2 000° C.

The mercury vapour molecules are highly ionized by collision with the electrons emitted from the cathode. The positive ions thus formed fall upon the cathode spot and by their continuous bombardment maintain its temperature at the high value corresponding to the incandescent state. At the same time, the presence of these positive ions above the cathode surface creates a positive space-charge there, which withdraws electrons from the mercury.

Arc Drop. The electrons emitted and withdrawn from the cathode, together with any electrons liberated as a result of ionization of the mercury vapour by collision, will travel towards an anode, provided its potential is some 20 to 30 volts positive with respect to the cathode. This voltage, generally known as the *arc drop* of the rectifier, represents energy lost in the arc and at the cathode and anode. The total drop actually comprises the drop at the surface of the cathode, the drop in the arc proper, and the drop at the surface of the anode. Of these, the cathode drop appears to be constant for all types of mercury-arc rectifier and practically independent of the load. It has an average value of about 7 volts, and represents energy which is consumed in liberating electrons from the cathode and in evaporating mercury. The voltage drop in the arc itself has a value of from 0·05 to 0·2 volts per centimetre, that is, in the neighbourhood of one-quarter of a volt per inch. This voltage drop represents energy spent in ionization of mercury vapour in the arc path by collision, and varies with the current output and temperature of the rectifier. The anode drop amounts to about 5 volts and is sensibly independent of the anode temperature, but varies with the material and configuration of the anode. It represents energy used up in overcoming the electric field in the vicinity of the anode (due to electrons crowding round the anode and bombarding the surface), which energy is dissipated as heat. The anode temperature is about the same as that of the cathode spot, namely, 500° to 700° C.; whilst the temperature of the arc has variously been estimated at from 1 000° to 10 000° C.

Ignition and Excitation. A characteristic feature of all arc rectifying devices is that the cathode spot has to be initiated by external means before an arc can be established. The initiation of a current arc in the rectifier is termed *ignition*, and is usually accomplished by drawing a small auxiliary arc between the cathode and an ignition electrode specially provided for this purpose. Furthermore, the independent existence of an arc, and therefore of the cathode spot, assumes in advance that the arc current does not fall below a certain minimum value necessary to maintain the temperature of the cathode spot. This critical value is normally about 3 amperes, but depends on the rectifier temperature and on the area of the cathode. In small rectifiers it may be as low as 1 ampere, while in the case of a large rectifier under cold conditions of operation it may reach as much as 10 amperes. In order to prevent the cathode spot from becoming extinguished at no-load, a small arc, called the *excitation arc*, is continuously maintained between the cathode and one or more auxiliary electrodes, known as *excitation anodes*. An interesting fact about such an excitation arc is that it enables the main anodes of the rectifier to deliver currents of very low magnitude, even as low as those required by a voltmeter.

CHAPTER III

THE FUNDAMENTAL MECHANISM OF ARC RECTIFICATION

The Meaning of Rectification. In applying the rectifying property of the arc discharge to the practical conversion of alternating to direct current, use is made of the commutation principle, which is the basis of so many electrical machines. The mercury-arc rectifier is, so far as its practical working is concerned, nothing other than a switching device which, by effecting a regular changing over of the electrical connections between an alternating-current supply circuit and a direct-current load circuit, ensures that the voltage applied to the latter is unchanging in its direction. In other words, the alternating impulses taken from the supply are modified by the rectifier either in such a way that one of the two directions of pulsation is suppressed; or else in such a way that every alternate impulse is reversed in direction. Rectifiers consequently deliver either an intermittent or a pulsating unidirectional current, that is, a pure direct current on which an alternating current is superimposed. As will be explained in a later chapter, the magnitude of this alternating component depends both on the number of rectifier phases and on the nature of the rectifier load.

In the case of a single-phase alternating-current supply (Fig. 6), the circumstances under which rectification is effected are relatively easy to understand. If we imagine the rectifier to operate so that connection is made between terminals 1 and 3 and between terminals 2 and 4 during one half-cycle, and that these connections are broken during the other half-cycle, then an intermittent but unidirectional current will flow from the alternating-current supply to the direct-current load circuit. Once in every cycle of alternating voltage this current will remain at zero value during a half-cycle. This process of energy transmutation is accordingly called *half-wave* rectification. Now, a little consideration will show that a better utilization of the voltage cycle is obtained if the rectifier operates so that, during one half-cycle, connection is made between terminals 1 and 3 and between terminals 2 and 4; whilst, during the other half-cycle, connection is made between terminals 1 and 4 and between terminals 2 and 3. In this way use is made of both half-waves of the alternating voltage; and the *modus operandi* of such a rectifier is consequently referred to as *full-wave* rectification. But even this process is capable of improvement. It labours under the disadvantage that a double-pole change-over of connection between the alternating-current and direct-current circuits is necessary. This defect may be remedied, however, by connecting a potential divider across the alternating-current supply and joining its mid-point to one pole of the direct-current system.

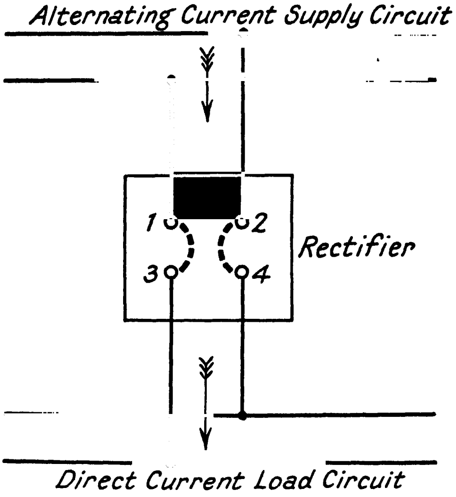
Alternating Current Supply Circuit
1
2
3
4
Rectifier
Direct Current Load Circuit

FIG. 6. FUNDAMENTAL PRINCIPLE OF RECTIFICATION

For reasons that will be explained in a later section of the present chapter, potential division is in practice effected by the secondary winding of a transformer having its primary winding connected to the alternating-current supply. The arrangement of such a single-phase full-wave rectifier is shown in Fig. 7A. In this diagram the rectifier is represented by a single-pole change-over switch. Again, a little consideration will show that if the switch is thrown over from one position into the other at the commencement of every half-cycle, then a pulsating but unidirectional current will flow in the direct-current circuit. That this must be so is fairly evident from the fact that, since the switch is made to move from the one position to the other just as rapidly as the voltage of the transformer secondary changes its direction, the fulcrum is always connected to that half of the transformer secondary in which both voltage and current have positive direction. A current will thus continue to flow from the fulcrum of the change-over switch, through the direct-current circuit, back to the neutral point of the transformer secondary. The pole of the direct-current system connected to the fulcrum of the change-over switch is thus the positive pole; that connected to the transformer neutral point is the negative pole. The voltage supplied from the rectifier is in this case a strongly pulsating one, varying at double frequency between zero and a maximum. On replacing the foregoing arrangement by a three-phase transformer and a switch having three contact positions, a rectified voltage is obtained which is considerably less undulating, but of triple frequency. Such a three-phase rectifying arrangement is illustrated by Fig. 7B. In the case of a transformer having six secondary phases, a rectified voltage of sextuple frequency is obtained in which the maximum deviation from the pure direct form amounts to only a few per cent, as is shown in a general way by Fig. 7C.

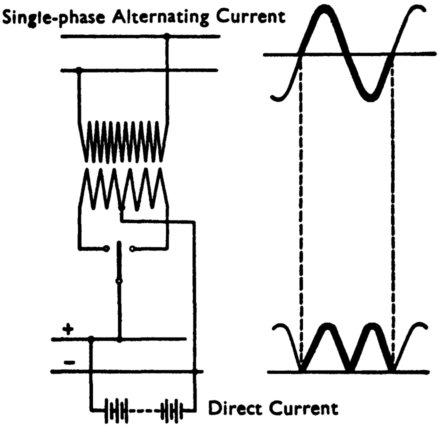

FIG. 7A. SINGLE-PHASE RECTIFICATION
English Electric Co.

Referring to Fig. 7C, the current arc in the mercury-arc rectifier represents the moving switch arm, with its fulcrum

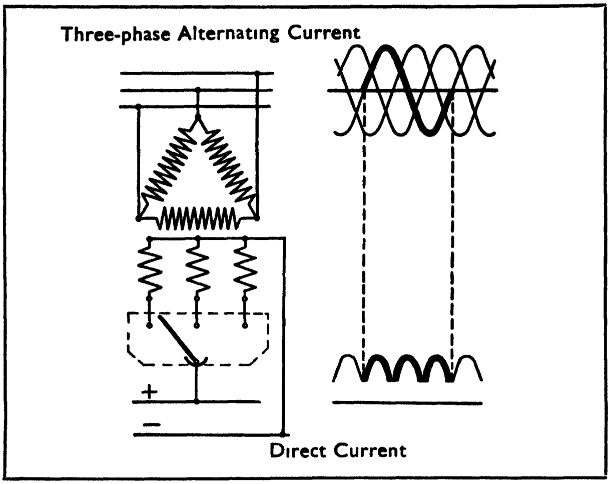

FIG. 7B. THREE-PHASE RECTIFICATION

English Electric Co

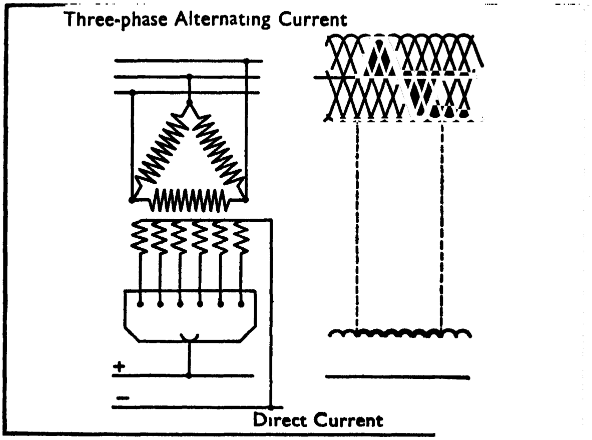

FIG. 7C. SIX-PHASE RECTIFICATION

English Electric Co.

at the cathode, whilst the fixed contacts of the switch are represented by the rectifier anodes. The latter are, of course, actually arranged in a circle above the cathode, and the current arc sweeps uniformly over them. The electrons emanating from the cathode are always directed to that anode which for the moment has the highest potential. The arc is, however, established at this anode only during such time as its potential is higher than that of the remaining anodes.

Phase Commutation. The unilateral conductivity of the current arc, together with the cyclic variation of successive phase voltages, provides an inherent and perfectly stable means of commutating the load current from one phase to the next. This process of current transfer is accordingly termed *phase commutation*. It takes place naturally, and is effected by the instantaneous voltage difference between the rectifier phases involved.

The conditions under which phase commutation takes place in the mercury-arc rectifier when converting alternating to direct current* are conveniently illustrated by reference to Fig. 8, in which e_1, e_2, etc., represent successive phase voltages (each of periodic time T) of a symmetrical p-phase rectifier system. Assuming phase 1 to be carrying the load current during the time interval T/p between the points O and P, it is seen that at the instant corresponding to the point K, its voltage is still higher than that of phase 2; so that the potential difference $(e_2 - e_1) = K'L'$ is in the direction opposed to the transfer of current from phase 1 to phase 2. At time $t = t_1$, corresponding to the point P, this potential difference becomes zero and both anodes have the same potential. Later still, at an instant corresponding to the point N', the potential difference $(e_2 - e_1) = M'N'$ is in the direction requisite to current transfer. Thereafter this potential difference increases, and then decreases until at time $t = t_2$, corresponding to the point Q in the negative half-cycle of anode voltage, both anodes again have the same potential. Commutation of the load current from phase 1 to phase 2 can thus take place at any point in the voltage cycle between P and Q. Assuming the current arc to commutate instantaneously, it will naturally tend to do so at the earliest possible instant in the anode voltage cycle, namely, at time $t = t_1$, corresponding to the point P. Phase commutation of this kind is often referred to as *natural commutation*, as distinct from *forced commutation* which takes place when the rectifier operates at reduced voltage, or as an invertor, by grid control (*cf.* Chapters X and XI).

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* Phase commutation is, as a rule, also employed to obtain inversion of direct to alternating current by means of the grid-controlled rectifier, i.e. in the case of the mercury-arc invertor.

Provided that the secondary winding of the rectifier transformer is symmetrical, phase commutation will result in a corresponding symmetry of the anode currents, i.e. the intermittent currents carried by the secondary phases of the rectifier

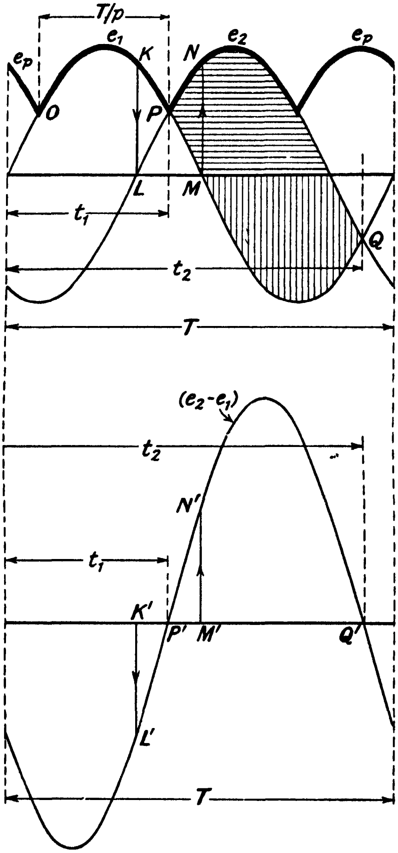

Fig. 8. Phase Commutation in the Mercury-arc Rectifier

transformer. Thus in the case of the ideal six-phase rectifier depicted in Fig. 7c, for example, each anode carries the entire load current of the rectifier during one-sixth of the voltage cycle. In practice, however, due to the reactance of the transformer, a certain amount of overlap or delay in the commutation of the current arc from one anode to the next takes place, so that the load current commences ~~to grow in any~~ one phase before it has completely died away in the preceding phase. ~~The significance of this characteristic rectifier~~ phenomenon is discussed towards the end of the present chapter.

Voltage Relations. From the foregoing considerations it is apparent, therefore, that the mercury-arc rectifier is to be regarded more in the nature of switchgear than of an electrical machine, the source of the e.m.f. being not the rectifier itself, but its accompanying transformer. Consequently, one would expect there to be a definite relation between the electrical ~~quantities on the alternating-current~~ and direct-current sides of the apparatus, and this is actually the case. The voltage and current relations can be expressed as fixed ratios determined solely by the number of rectifier phases. And their evaluation in as simple a manner as possible is of the greatest importance to the understanding of rectifier circuit theory.

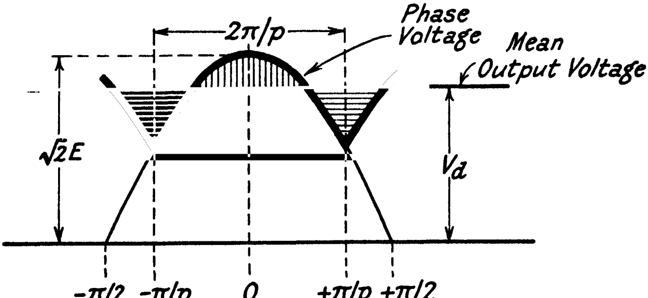

FIG. 9. VOLTAGE RELATIONS

The relation between the voltages on the input and output sides of the rectifier is shown diagrammatically in Fig. 9, relating to a theoretically perfect rectifier system having p phases. During every cycle each phase operates during a period ~~corresponding to $2\pi/p$ radians~~, or $360/p$ electrical degrees. ~~It is seen~~ that the output voltage is the average value of a cosine wave of amplitude $(\sqrt{2})E$ between ordinates erected at ~~a distance π/p on~~ either side of the time-origin of the abcissae. Its magnitude in terms of the r.m.s. phase voltage E is, therefore, given by

$$V_d = E \,.\, \sqrt{2}\frac{p}{2\pi}\int_{-\pi/p}^{+\pi/p} \cos\theta \,.\, d\theta = E \,.\, \sqrt{2}\frac{p}{\pi}\sin\frac{\pi}{p} \quad . \quad . \quad (1)$$

Current Relations. In the ideal case here considered, the rectifier delivers a pure direct current. As this output current is the sum total of the successive phase currents, it follows that the input current of each phase must have a rectangular wave-form. The corresponding current relations are shown diagrammatically in Fig. 10. The conditions obtaining in practice are actually not much different from those illustrated by this diagram, for the influences tending to produce a deviation from the rectangular wave-form tend also to give rise to bad voltage regulation of the rectifier as well as harmonics in the output voltage, and it is precisely these tendencies which it is desirable to avoid in practical rectifier installations.

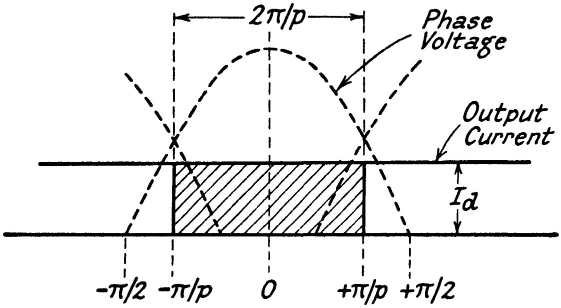

FIG. 10. CURRENT RELATIONS

The rectangular phase-current wave can be resolved into its fundamental and harmonic components, these being all cosine functions of the usual form

$$a_n \cos n\theta$$

between the limits $\theta = -\pi/p$ and $\theta = +\pi/p$. The amplitude of the nth harmonic is thus

$$a_n = I_d \cdot \frac{1}{\pi}\int_{-\pi/p}^{+\pi/p} \cos n\theta \, . \, d\theta = \frac{2Id}{n\pi} \, . \sin\frac{n\pi}{p} \quad . \quad . \quad . \quad (2)$$

Of more importance, however, are the average and effective values of the input current to the rectifier. The mean value is, of course, I_d/p; whilst the r.m.s. value is $I = I_d/\sqrt{p}$. Table I (page 34) gives these two current values for different numbers of rectifier phases expressed in terms of the output current I_d. The last line of the table shows the total r.m.s. value of all the harmonics given by the expression $I_d\sqrt{(1/p - 1/p^2)}$.

Utility Factor of the Rectifier. Having established the relations between the respective voltages and currents on th alternating-current and direct-current sides of the rectifier, i is instructive to consider finally the corresponding relatio between the input and output powers.

Assuming, as before, an r.m.s. phase voltage E, a stead output current I_d, and p rectifier phases, then the apparen r.m.s. volt-amperes supplied to the rectifier are given by

$$P_a = p \, . \, EI$$

whilst the equivalent power output from the rectifier is given b

$$P = V_d \, . \, I_d$$

The ratio P/P_a is a measure of the degree to which the rectifie

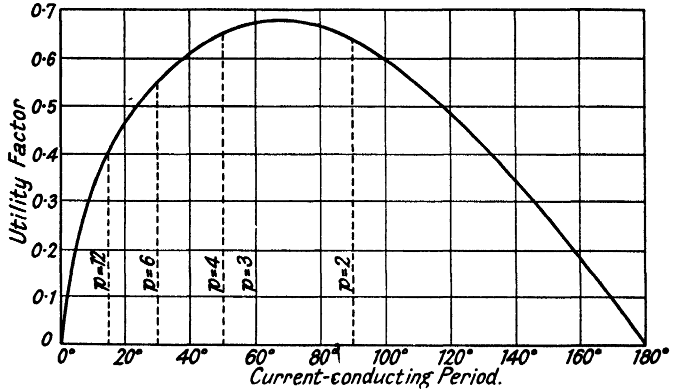

FIG. 11. RELATION BETWEEN UTILITY FACTOR AND CURRENT-CONDUCTING PERIOD

is capable of utilizing and converting the energy supplied to it, and is accordingly referred to as the *utility factor*. Its value is thus

$$\frac{P}{P_a} = \frac{1}{p} \cdot \frac{V_d}{E} \cdot \frac{I_d}{I} = \frac{1}{p} \cdot \frac{p\sqrt{2}}{\pi} \sin\frac{\pi}{p} \cdot \sqrt{p}$$

$$= \frac{\sqrt{(2p)}}{\pi} \cdot \sin\frac{\pi}{p} = \left(\sqrt{\frac{2}{\pi}}\right) \cdot \frac{\sin\Theta}{\sqrt{\Theta}} \quad . \tag{3}$$

where $\Theta = \pi/p$, that is, half the current-conducting period per phase. The relation is shown graphically in Fig. 11. It is seen that the maximum degree of utilization is obtained with $\Theta = 66° \, 48'$, corresponding to $p = 2{\cdot}69$. In an actual rectifier it is, of course, only possible to obtain values of $\Theta = \pi/p$, in which p is an integer. So that, for a given kVA input, the nearest approach to the maximum output power theoretically possible is obtained with simple three-phase rectification; whilst both single-phase and two-phase full-wave rectifiers allow of very nearly the same degree of utilization.

In the following chapters, dealing with the rating of rectifier transformers, the importance of the utility factor in determining the most economical arrangement of the transformer windings will become apparent. Suffice it to say here that, as may be seen from Fig. 11, the utility factor is invariably less than unity. The reason for this fact is to be sought in the difference between the input voltage and current wave-forms. The former is sinusoidal, whilst the latter is rectangular; so that the apparent input power is of necessity greater than the actually converted power by an amount equal to the wattless, non-reactive power lost in generating the harmonics required so that the rectifier may deliver a pure direct current.* It should be noted, also, that in the simple types of rectifier circuit shown in Fig. 7 the currents flowing in the secondary windings of the transformer are identical with the input currents to the rectifier, so that the utility factor of the transformer secondary is then the same as that of the rectifier itself. In the case of the primary winding, however, each phase is utilized twice in every voltage cycle. The currents flowing in the primary winding thus consist of rectangular blocks of current similar to those in the secondary winding, but only 180 electrical degrees apart, the alternate blocks being of opposite sign. The heating effect of such a current will be twice that of a current consisting of pulses in one direction only, and the r.m.s. value of the primary current will therefore be $\sqrt{2}$ times that of the equivalent secondary current. Consequently the utility factor of the primary winding will be greater than that of the secondary winding by 41 per cent.

The Effect of Transformer Reactance. As will be explained in the next chapter, the method of analysis there developed, and subsequently adopted for evaluating the important rectifier transformer data, involves certain simplifying assumptions, the necessity for which does not detract materially from the results obtained. These assumptions have been made for two very good reasons; firstly, in order that the method might not be obscured by the welter of mathematics inseparable from a rigorous treatment of the rectifier problem; and, secondly, in order to reduce the actual labour of calculation.

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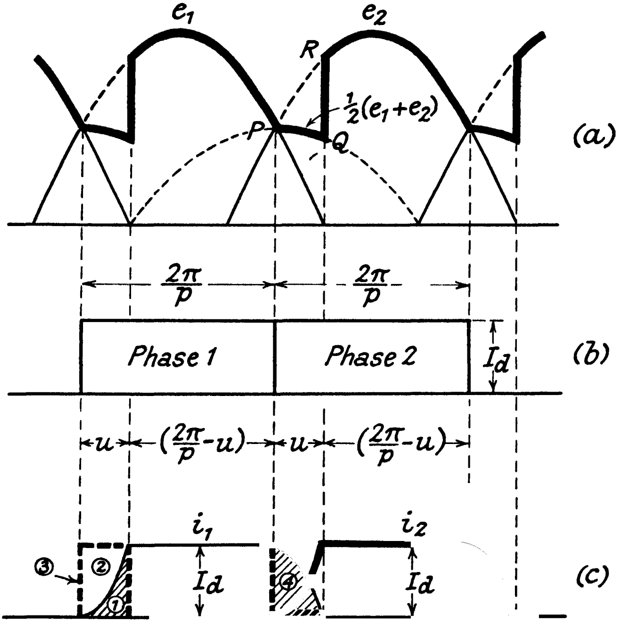
* *Vide* Chapter XIV.

Of such assumptions, the most important from both these points of view is that which neglects the inductive effect of the rectifier transformer windings. By thus leaving the question of transformer reactance out of our calculations, it follows that the individual anode current waves are rectangular in shape. This theoretical assumption of instantaneous arc commutation from one anode to the next allows any calculations based upon it to be approximate only, although the approximation is sufficiently close for most practical purposes. But to arrive at accurate values for the currents and voltages in rectifier circuits, it is necessary to take into account the reactance of the rectifier transformer windings. Due to this reactance a definite time is required for the anode current to rise to its full value at the start of each conducting period, and again to fall to zero at the end of the conducting period. As the result, the anode current wave is altered from the form shown in Fig. 12 (*b*) and assumes the shape as indicated by the full lines of Fig. 12 (*c*). The corresponding change in waveform of the rectified voltage is shown by Fig. 12 (*a*).

It is seen that anode 1 carries the full direct current I_d until the point P in its voltage cycle is reached when the voltages e_1 and e_2 of anodes 1 and 2 are equal, at which point anode 2 starts to pick up the current arc. Due to the inductive effect of the transformer windings, the arc is not immediately transferred, but anode 1 continues to carry current. For a short interval of time both anodes remain at the same potential, namely, the mean of e_1 and e_2, as shown in Fig. 12 (*a*). During this brief interval the current carried by anode 1 gradually falls away to zero; whilst that carried by anode 2 increases similarly until, at the end of the interval, it attains the value I_d, and anode 1 no longer carries any current. At this instant the voltage of anode 2 jumps from the value $\frac{1}{2}(e_1 + e_2)$, corresponding to the point Q in Fig. 12 (*a*), to the full value e_2, corresponding to the point R.

The conditions under which this *overlap* of the anode currents, as it is called, takes place are readily understood by considering the circuit voltages during the interval. Referring to Fig. 13, at the instant corresponding to the point of intersection of e_1 and e_2, anodes 1 and 2 are connected simultaneously to the cathode, and thus together constitute an electrical connection between the corresponding phases of the transformer secondary, short-circuiting the difference in voltage between these two overlapping phases. This difference in voltage produces an increasing short-circuit current which circulates round



① + ② = ③ = ① + ④

FIG. 12. EFFECT OF TRANSFORMER REACTANCE

the loop thus formed and flows in a direction opposed to the direct current carried by anode . causing the latter to decrease. With reference to anode 2, however, this circulating current is in the same direction as the direct current, so that the current carried by that anode naturally increases during the interval of overlap. This state continues until the instantaneous value of the circulating current equals the direct current previously carried by anode 1, when the resultant current carried by that anode is zero and the arc is extinguished. Extinction of the arc at anode 1 terminates the short-circuit between the overlapping phases leaving anode 2 carrying the full direct current I_d, and commutation of the current arc is complete. This

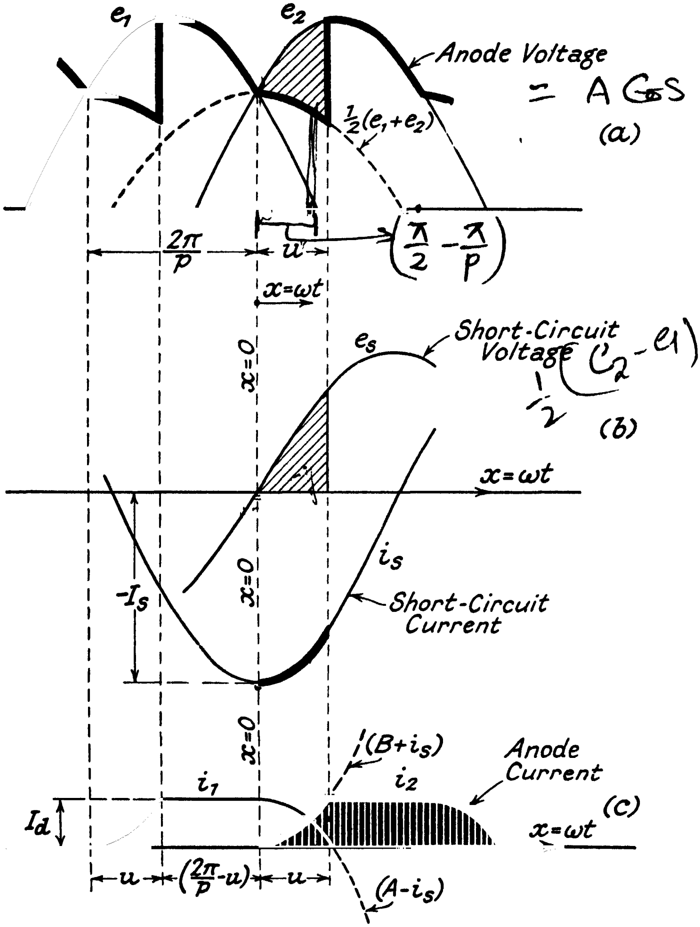


FIG. 13. EFFECT OF TRANSFORMER REACTANCE (*contd.*)

period of commutation is expressed by the *angle of overlap u* indicated in Figs. 12 (*b*) and 13.

It is evident that the most important effect of transformer reactance is a reduction in the output voltage from the rectifier

The reactive voltage drop is represented by the area *PQR* in Fig. 12 (*a*), shown shaded in Fig. 13. During the period of overlap (u), the net rectified voltage is equal to the mean of the successive phase voltages, whilst during the remainder of the conducting period ($2\pi/p - u$) it is equal to the instantaneous voltage of the working phase. Referring to Fig. 13, and taking as origin the instant corresponding to the point of intersection of e_1 and e_2, the output voltage from the rectifier is therefore given by

$$\begin{aligned}
V_d &= \frac{p}{2\pi}\left[\int_0^u \tfrac{1}{2}(e_1 + e_2)\,.\,dx + \int_u^{2\pi/p} e_2\,.\,dx\right] \\
&= \frac{p}{2\pi}\,.\,(E\sqrt{2})\left[\int_0^u \tfrac{1}{2}\left\{\cos\left(x + \frac{\pi}{p}\right) + \cos\left(x - \frac{\pi}{p}\right)\right\}.\,dx \right. \\
&\qquad \left. + \int_u^{2\pi/p} \cos\left(x - \frac{\pi}{p}\right).\,dx\right] \\
&= \frac{p}{2\pi}\,.\,(E\sqrt{2})\left[\cos\frac{\pi}{p}\,.\,\sin u + \sin\frac{\pi}{p} - \sin\left(u - \frac{\pi}{p}\right)\right] \\
&= \frac{p}{2\pi}\,.\,(E\sqrt{2})\left[\sin\frac{\pi}{p}\,(1 + \cos u)\right] \\
&= (E\sqrt{2})\,.\,\frac{p}{\pi}\sin\frac{\pi}{p}\,.\,\cos^2\frac{u}{2} \qquad (4)
\end{aligned}$$

Comparing this result with that of equation (1), it may be expressed in the form

$$V_d = V_{d_0}\,.\,\cos^2\frac{u}{2} \qquad (4a)$$

where V_{d_0} is the output voltage of the rectifier when the effect of transformer reactance is neglected, i.e. the output voltage at no-load. The drop in output voltage due to transformer reactance is thus given by

$$\varepsilon_r = V_{d_0}\,.\,\sin^2\frac{u}{2} = V_{d_0} - V_d \qquad (4b)$$

The relation expressed by (4*b*) is of paramount importance in rectifier design and is shown in Fig. 14.

It remains to be shown that the angle of overlap u is a function of the rectifier load, that is, of the current output I_d.

As already mentioned, the current circulating round the loop

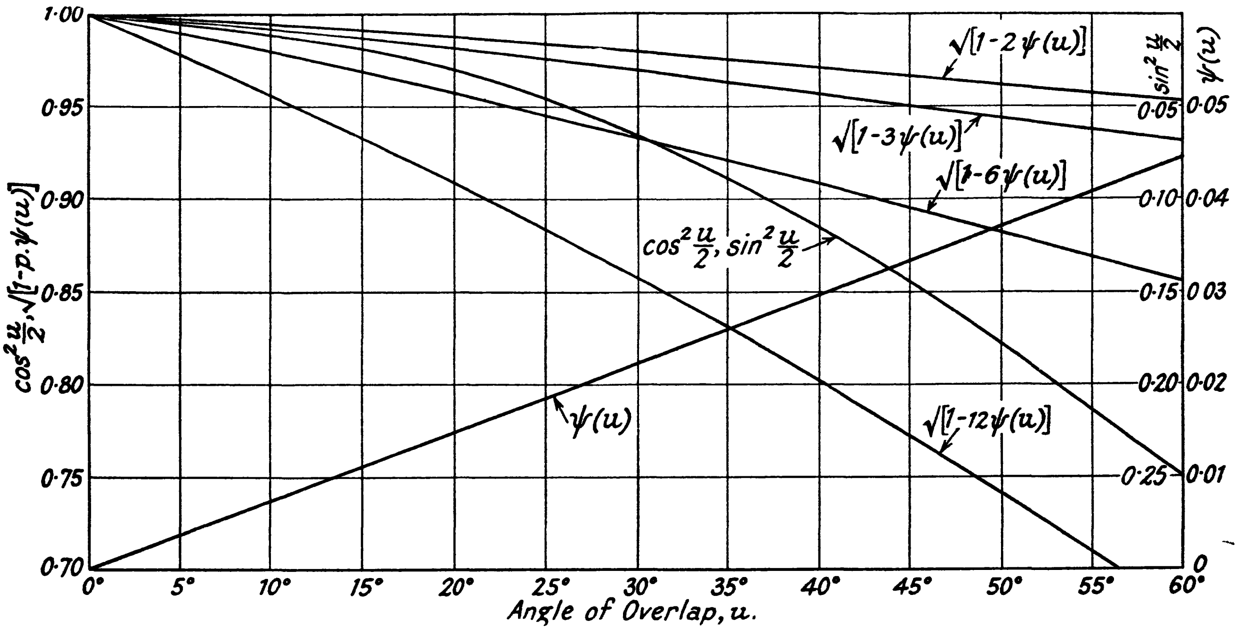


FIG. 14. VALUES OF FACTORS INVOLVING ANGLE OF OVERLAP u

formed by the electrical connection of phases 1 and 2 is produced by the instantaneous difference between the phase voltages e_1 and e_2. The reactance voltage per phase during the ~~period of overlap is thus~~

$$e_s = \tfrac{1}{2}(e_2 - e_1) = \frac{E\sqrt{2}}{2} . \left[\cos\left(x - \frac{\pi}{p}\right) - \cos\left(x + \frac{\pi}{p}\right)\right]$$
$$= E\sqrt{2} . \sin\frac{\pi}{p} . \sin x \qquad . \quad . \quad . \quad . \quad . \qquad (5)$$

If the effective reactance per secondary phase* be denoted by X, then the short-circuit current during the period of overlap will be $i_s = e_s/X$, and will have an amplitude $I_s = (E\sqrt{2}/X) . \sin(\pi/p)$.† As this short-circuit current is purely inductive, it lags 90 electrical degrees behind the short-circuit voltage, as shown in Fig. 13, so that

$$i_s = I_s . \sin\left(x - \frac{\pi}{2}\right) = -I_s . \cos x \qquad . \quad . \qquad (5a)$$

During the period of overlap the anode currents i_1 and i_2 differ from the short-circuit current i_s only ~~by constant~~ direct-current components, so that, referring to Fig. 13, we may write

$$\left.\begin{aligned} i_1 &= A - i_s = A + I_s . \cos x \\ \text{and} \qquad i_2 &= B + i_s = B - I_s . \cos x \end{aligned}\right\} \qquad . \quad . \qquad (6)$$

The constants A and B are determined from the conditions that $i_1 = I_d$ and ~~$i_2 = 0$~~ when $x = 0$, which gives $A = (I_d - I_s)$ and $B = I_s$. Hence for $0 < x < u$ we obtain

$$\left.\begin{aligned} i_1 &= I_d - I_s . (1 - \cos x) \\ \text{and} \qquad i_2 &= I_s . (1 - \cos x) \end{aligned}\right\} \qquad . \quad . \quad . \qquad (6a)$$

The value of the angle of overlap u in terms of the circuit constants is determined from the conditions that $i_1 = 0$ and $i_2 = I_d$ when $x = u$, either of which gives

$$\cos u = 1 - \frac{I_d}{I_s} = 1 - \frac{I_d X}{E\sqrt{2} . \sin(\pi/p)} \qquad . \qquad (7)$$

---

* I.e. the reactance due not only to the inductance of the secondary winding itself, but also to the equivalent inductance (referred to the secondary) of the primary winding together with that of the alternating-current supply.

† Strictly speaking the amplitude I_s is not constant, but decreases exponentially on account of the inevitable resistance in the circuit. Such resistance effects, however, are of only secondary importance, and need not be considered here.

or, alternatively,

$$\sin\frac{u}{2} = \sqrt{\left[\frac{I_d X}{(2E\sqrt{2}) \, . \sin(\pi/p)}\right]} \quad . \quad . \quad . \quad (7a)$$

It is seen, therefore, that the angle of overlap increases with load: also, if the value of u given by (7*a*) is substituted in equation (4*b*), it is found that the drop in output voltage occasioned by transformer reactance is similarly a function of the rectifier load, the relation in this case being linear. We therefore arrive at the important conclusion that the mercury-arc rectifier inherently possesses a *straight shunt* voltage characteristic, a fact which is of considerable moment from the point of view of rectifier operation.

Finally, it is necessary to determine the influence of the overlapping of the anode currents upon their r.m.s. value. In the first place it should be noted that the effect of reactance is to increase, by the angle u, the period during which each anode carries current, without altering either the maximum or the average* value of the anode current. As the result, it is to be expected that the effective value of the anode current is decreased.

Referring again to Fig. 13, it is seen that the anode current consists of three parts: two parts, each extending over the angle u, and expressed by

$$i_1 = I_d \, . \frac{\cos x - \cos u}{1 - \cos u}$$

and

$$i_2 = I_d \, . \frac{1 - \cos x}{1 - \cos u}$$

as derived from equations (6*a*) and (7); and a third, intermediate part of constant value I_d, extending over an angle $(2\pi/p - u)$. The r.m.s. value I of the anode current is therefore given by

$$\begin{aligned} 2\pi I^2 &= \int_0^u i_1^2 \, . \, dx + I_d^2\left(\frac{2\pi}{p} - u\right) + \int_0^u i_2^2 \, . \, dx \\ &= I_d^2\left\{\frac{2\pi}{p} - 2\int_0^u\left[\frac{1 - \cos x}{1 - \cos u} - \left(\frac{1 - \cos x}{1 - \cos u}\right)^2\right] . \, dx\right\} \\ &= I_d^2 \, . \frac{2\pi}{p}\left[1 - p \, . \, \psi(u)\right] \end{aligned}$$

---

* As may be seen from Fig. 12 (*c*), the loss in average value represented by the area 2 is equal to the gain represented by the area 4.

so that

$$I = \frac{I_d}{\sqrt{p}} . \sqrt{[1 - p . \psi(u)]} \quad . \quad . \quad . \quad . \qquad (8)$$

where

$$\psi(u) = \frac{1}{\pi}\int_0^u \left[\frac{1 - \cos x}{1 - \cos u} - \left(\frac{1 - \cos x}{1 - \cos u}\right)^2\right] . dx$$

$$= \frac{(2 + \cos u)\sin u - (1 + 2\cos u)u}{2\pi(1 - \cos u)^2} \quad . \quad . \qquad (9)$$

For values of u between 0 and $\pi/2$, the function represented by (9) may conveniently be expressed as a series

$$\psi(u) = \frac{2u}{15\pi}\left(1 + \frac{u^2}{84} + \ . \ . \ . \ \right) . \quad . \quad . \quad . \quad . \qquad (9a)$$

As may be seen from Fig. 14, this function is almost linear with respect to u.

The effect of reactance in the rectifier transformer is thus to reduce the r.m.s. value of the anode current by the factor $\sqrt{[1 - p . \psi(u)]}$. This factor is also shown in Fig. 14, plotted as a function of u, for 2, 3, 6 and 12 phases.

TABLE I

HARMONIC COMPONENTS OF RECTANGULAR ANODE-CURRENT WAVES IN TERMS OF I_d

Number of rectifier phases . .	2	3	4	6	12
Mean value of the input current . .	0·500	0·333	0·250	0·167	0·083
R.M.S. value of the input current .	0·707	0·577	0·500	0·408	0·289
Amplitude of the fundamental . .	0·637	0·552	0·450	0·318	0·165
,, ,, 2nd harmonic . .	—	0·276	0·318	0·276	0·159
,, ,, 3rd ,, . .	0·212	—	0·150	0·212	0·150
,, ,, 4th ,, . .	—	0·138	—	0·138	0·138
,, ,, 5th ,, . .	0·127	0·110	0·090	0·064	0·123
,, ,, 6th ,, . .	—	—	0·106	—	0·106
,, ,, 7th ,, . .	0·091	0·079	0·064	0·045	0·088
R.M.S. value of all harmonics . .	0·500	0·471	0·433	0·373	0·276

The Effects of Arc Drop and Transformer Resistance. Up to the present we have considered only the effect of transformer reactance, and have neglected both the arc drop in the rectifier and the resistance of the transformer windings. These are of

TABLE II

No. of Phases		Connection of Rectifier System	kVA/kW Ratio		Phase Equal'r Rating	Mean Rating W/W_d	Utility Factor W_d/W	Line kVA W_L/W_d	Distor'n Factor W_d/W_L	Ratio V_{d_0}/E	
Primary	Secondary		W_2/W_d	W_1/W_d						F.L.	N.L.
1	2	1-phase full-wave	1·57	1·11	—	1·34	0·746	1·11	0·90	0·90	0·90
3	3	3-phase half-wave	1·48	1·48	—	1·48	0·675	1·21	0·79	1·17	1·17
3	3	3-phase inter-star	1·71	1·21	—	1·46	0·685	1·21	0·79	1·17	1·17
2	4	2-phase full-wave	1·57	1·11	—	1·34	0·746	1·11	0·90	1·27	1·27
3	6	3-phase full-wave	1·82	1·29	—	1·55	0·645	1·05	0·95	1·35	1·35
3	6	6-phase fork	1·79	*1·05	—	1·42	0·704	1·05	0·95	1·35	1·35
3	6	Double 3-phase	1·48	*1·05	$\frac{1}{12}W_d$	1·35†	0·741	1·05	0·95	1·17	1·35
3	6	Triple 1-phase	1·57	1·11	$\frac{1}{4}W_d$	1·59†	0·629	1·05	0·95	0·90	1·35
3	12	12-phase fork	2·17	1·08	—	1·63	0·615	1·01	0·99	1·40	1·40
3	12	Quadruple 3-phase	1·65	*1·01	$\frac{3}{32}W_d$	1·42†	0·704	1·01	0·99	1·17	1·40
3	12	Triple 4-phase	1·61	1·02	$\frac{1}{32}W_d$	1·35†	0·741	1·01	0·99	1·27	1·40
3	12	Double 6-phase	1·86	1·05	$\frac{1}{96}W_d$	1·47†	0·682	1·01	0·99	1·35	1·40
3	12	12-phase series	1·67	1·03	—	1·35	0·741	1·03	0·97	1·27	1·27

* With either star-connected or delta-connected primary winding.

† Including phase equalizer(s).

no importance as far as limitation of current values is concerned, but they have an appreciable bearing on the output voltage of the rectifier. The values given by equation (4*a*) apply to the ideal case of a rectifier unit devoid of all losses. In practice, it is, of course, necessary to take into account the copper losses in the transformer as well as the arc loss in the rectifier itself, when calculating the net voltage delivered at the direct-current terminals of the rectifier unit. Consequently we may write

$$V_d = V_{d_0} - \varepsilon_r - \varepsilon_c - \varepsilon_a \quad . \quad . \quad . \quad (10)$$

where ε_r = voltage drop due to transformer reactance,

ε_c = voltage drop due to transformer copper loss,

and ε_a = voltage drop due to the arc loss.

Here V_{d_0} is the no-load output voltage of the rectifier unit as given by equation (1).

If W_c denote the transformer copper loss, then the drop in the output voltage occasioned by this loss is $\varepsilon_c = W_c/I_d$. Moreover, the voltage delivered at the direct-current terminals at no-load is $(V_{d_0} - \varepsilon_a)$, so that the overall regulation of the rectifier unit is

$$r\% = 100 \times \left(1 - \frac{V_d}{V_{d_0} - \varepsilon_a}\right) = 100 \times \left(\frac{\varepsilon_r + \varepsilon_c}{V_{d_0} - \varepsilon_a}\right) \quad (11)$$

CHAPTER IV

RECTIFIER CIRCUIT THEORY

In this and the following two chapters the voltage and current relations previously established for the rectifier circuit in its most elementary form are applied to practical rectifier connections. The method of analysis here adopted allows the required circuit data to be evaluated in a relatively simple manner from diagrams which serve, at the same time, to provide an insight into the peculiar conditions of current-flow in the various parts of the circuit; that is to say, in the different windings of the rectifier transformer as well as in the alternating-current supply system.

General Considerations. In order to reduce the problem to its simplest form, it is convenient, at the outset, to make the following basic assumptions—

1. The rectifier output is considered to be a pure direct current, so that the anode currents are then of rectangular wave-form.
2. The effects of transformer reactance and magnetic leakage are ignored.
3. The influences of the arc drop in the rectifier and of the copper loss in the transformer upon the output voltage are neglected.
4. The alternating-current supply voltage is assumed to be sinusoidal under all conditions of rectifier loading.
5. The magnetizing current of the rectifier transformer is assumed to be negligible.

Of these assumptions, the first is the most important by far. It greatly simplifies the analysis, and does not detract from the value of the results obtained except in the case of single-phase rectification and, possibly, in the case of three-phase rectification also. In practice, of course, the current delivered by the rectifier is undulating, the degree of undulation depending upon the ratio of resistance to reactance in the direct-current load circuit; whilst, for a given value of this ratio, the undulation decreases with increase in the number of rectifier phases, as shown diagrammatically in Fig. 7. Consequently the difference between the mean and r.m.s. values of the anode current due to non-linearity of the output current becomes appreciable only in single-phase rectifiers ($p = 2$) and, to a lesser extent, in three-phase rectifiers ($p = 3$), whilst in rectifiers for which $p \geqq 4$ the difference between the assumed rectangular anode-current wave-form and the actual wave-form occurring in the case of say a pure resistance load is no longer noticeable. To allow for this difference, however, it is in practice necessary to increase the current values and kVA ratings for the transformer windings by 11·1 per cent for single-phase rectifiers, and by 1·6 per cent for three-phase rectifiers.[*]

As far as the second assumption is concerned, the voltage and current values may be corrected to allow for overlapping of the anode currents by applying the appropriate formulae developed towards the end of Chapter III. As regards the third assumption, the output voltage may similarly be corrected so as to take into account these additional losses. The fourth assumption is self-evident and would appear to be justified in practice. At any rate, the deviations from the sinusoidal wave-form which arise in the supply voltage of large undertakings have not as yet made themselves felt in the sphere of rectifier operation, although it is by no means a foregone conclusion that this fortuitous situation will continue indefinitely.[†] The last assumption is of relatively minor importance. In any case, the effect of magnetizing current is the same in rectifier transformers as in ordinary power transformers. Being itself of low power factor, the magnetizing

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[*] The assumption of a pure direct current leads to an r.m.s. anode current which is $1/\sqrt{p}$ times the output current. In the case of a resistance load, for which the anode-current wave is no longer a rectangle but the central section of a sinusoidal half-wave, the ratio becomes

$$\frac{\pi}{p\,.\,\sin(\pi/p)}\sqrt{\left(\frac{1}{2p}+\frac{1}{4\pi}\sin\frac{2\pi}{p}\right)}$$

To make allowance for this extreme case, which may sometimes be approached very closely in practice, the r.m.s. value of the anode current must therefore be multiplied by the factor

$$\frac{\pi}{\sqrt{p}\,.\,\sin(\pi/p)}\sqrt{\left(\frac{1}{2p}+\frac{1}{4\pi}\sin\frac{2\pi}{p}\right)}$$

On calculation it will be found that for values of p greater than 4 this factor is indistinguishable from unity.

[†] The effects of non-sinusoidal voltage wave-form are dealt with in a paper by the author entitled: "The Influence of Mercury-Arc Rectifiers upon the Power-Factor of the Supply System," and published in the *I.E.E. Journal*, 1933, Vol. 72, p. 435.

current reduces the power factor of the rectifier unit, particularly at light loads.

The following nomenclature is adopted throughout this and the two subsequent chapters—

I_d = Mean direct current delivered by the rectifier at full load.

V_{d_0} = Mean no-load voltage at the secondary terminals of the rectifier transformer, as given by equation (1).

ε_a = Arc voltage drop in the rectifier.

$(V_{d_0} - \varepsilon_a)$ = Mean no-load voltage at the rectifier terminals.

V_d = Mean full-load voltage at the rectifier terminals.

I_1 = R.M.S. *anode* current (i.e. current flowing in outer stretches of the secondary winding of the rectifier transformer).

E_1 = R.M.S. alternating voltage per outer stretch of secondary.

I_2 = R.M.S. *secondary* current (i.e. current flowing in inner stretches of the secondary winding of the rectifier transformer).

E_2 = R.M.S. alternating voltage per inner stretch of secondary.

p = Number of rectifier phases.

E = R.M.S. secondary phase voltage at no-load.

I' = R.M.S. primary current at full load.

E' = R.M.S. primary phase voltage.

I_L = R.M.S. line current at full load.

E_L = R.M.S. line voltage.

W_2 = Secondary copper loading.

W_1 = Primary copper loading.

W = Mean kVA rating of rectifier transformer $(= [W_1 + W_2]/2)$.

W_L = Line kVA or kVA input to rectifier transformer.

W_d = kW input to rectifier $(= V_{d_0} . I_d)$.

U.F. = Utility factor of rectifier transformer $(= W_d/W)$.

μ_0 = Primary distortion factor* $(= W_d/W_L)$.

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* *Vide* Chapter XIV.

The principal results of the investigations contained in the next three chapters are collected together in Table II.

Single-phase Full-wave Rectification. As explained at the commencement of Chapter III, the full-wave circuit represents the most efficient system of rectification in the case of a single-phase alternating-current supply. It is, in fact, a simple two-phase system, with $p = 2$, so that the secondary phase voltage, as given by equation (1), is

$$E = \frac{\pi}{2\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/2)} = 1{\cdot}11\, V_{d_0} \quad . \quad . \quad . \quad (12a)$$

The anode (and secondary) current distribution is shown diagrammatically in Fig. 15 (*a*). During the first half-period

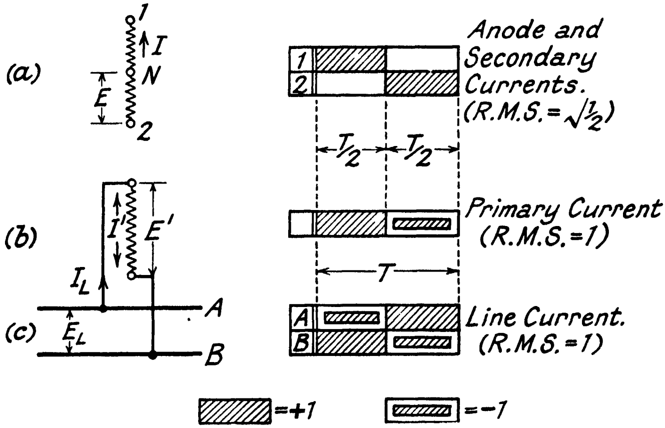

FIG. 15. SINGLE-PHASE FOUR-WAVE RECTIFICATION

the full direct current flows from the neutral N to anode 1; whilst during the second half-period this current flows in the opposite sense, from the neutral point to anode 2. The two conditions are represented by the shaded areas in the diagram. The r.m.s. value of the anode current is thus equal to that of a constant current I_d flowing for one half-cycle, and is therefore

$$I = \sqrt{\frac{(1)^2}{2}} \, . \, I_d = 0{\cdot}707 I_d \quad . \quad . \quad . \quad . \quad (12b)$$

The primary current distribution is similarly shown in Fig. 15 (*b*). When current flows in phase 1 of the secondary winding, an equivalent current flows in the primary winding.

Furthermore, this current must be of such magnitude and direction that the ampere-turns produced by it are equal and opposite to the secondary ampere-turns. In the other half-period, when current flows in phase 2 of the secondary winding, the equivalent primary current has the same magnitude as before, but reverses its direction, i.e. its value is now negative where before it was positive.

The secondary winding thus carries blocks of current which are always directed from the neutral point to the rectifier anodes; whilst the primary winding carries corresponding blocks of current which reverse their direction in alternate half-cycles. In other words, *the currents flowing in the secondary winding of a rectifier transformer are direct currents; and those flowing in the primary winding are alternating currents.*

The ratio of primary to secondary phase current is E/E', so that the r.m.s. value of the primary current is

$$I' = \sqrt{\left[\frac{(1)^2 + (-1)^2}{2}\right]} \cdot I_d \cdot \frac{E}{E'} = I_d \cdot \frac{E}{E'} \quad . \quad . \quad (12c)$$

As in this simple case the primary phase voltage E' is equal to the line voltage E_L, the r.m.s. value of the line current—the distribution of which is shown diagrammatically in Fig. 15 (*c*)—is therefore

$$I_L = \sqrt{\left[\frac{(-1)^2 + (1)^2}{2}\right]} \cdot I_d \cdot \frac{E}{E'} = I_d \cdot \frac{E}{E'} \quad . \quad (12d)$$

Secondary Copper Loading. From Fig. 15 (*a*) it is seen that the kVA rating of the secondary winding is

$$W_2 = 2EI = 2{\cdot}22 V_{d_0} \times 0{\cdot}707 I_d = 1{\cdot}57 W_d \quad . \quad . \quad (12e)$$

Primary Copper Loading. Similarly from Fig. 15 (*b*) it is seen that the kVA rating of the primary winding is

$$W_1 = E'I' = E' \cdot I_d \cdot \frac{E}{E'} = I_d \times 1{\cdot}11 V_{d_0} = 1{\cdot}11 W_d \quad (12f)$$

A.C. Supply Loading. From Fig. 15 (*c*) the line kVA input is

$$W_L = E_L I_L = E' I_L = E' \cdot I_d \cdot \frac{E}{E'} = 1{\cdot}11 W_d \quad . \quad . \quad (12g)$$

As mentioned on page 38, under normal conditions of rectifier operation the anode current is not really rectangular, but approaches more to a sinusoidal half-wave. As the result, the above kVA ratings have to be corrected to allow for the difference between its mean and r.m.s. values. The appropriate correction is obtained through multiplication by the factor 1·111; so that the true current values and kVA ratings become

$$I = 0{\cdot}786 I_d; \quad I' = 1{\cdot}11 I_d \cdot \frac{E}{E'}; \; I_L = 1{\cdot}11 I_d \cdot \frac{E}{E'};$$

$$W_2 = 1{\cdot}745 W_d; \; W_1 = 1{\cdot}235 W_d; \; W_L = 1{\cdot}235 W_d \quad . \quad (12h)$$

Three-phase Rectification (with Star-connected Secondary). The three-phase half-wave circuit (Fig. 16) represents the simplest rectifier connection possible where a three-phase alternating-current supply is available, but there are objections to its use in practice. On account of the half-wave rectification occurring in all three secondary phases, each primary phase can carry current during one half-cycle only, resulting in static magnetization of the core. Apart from this objectionable feature, the system can only be employed with a delta-connected primary winding. With star-connection on the primary side, when any one primary phase takes current

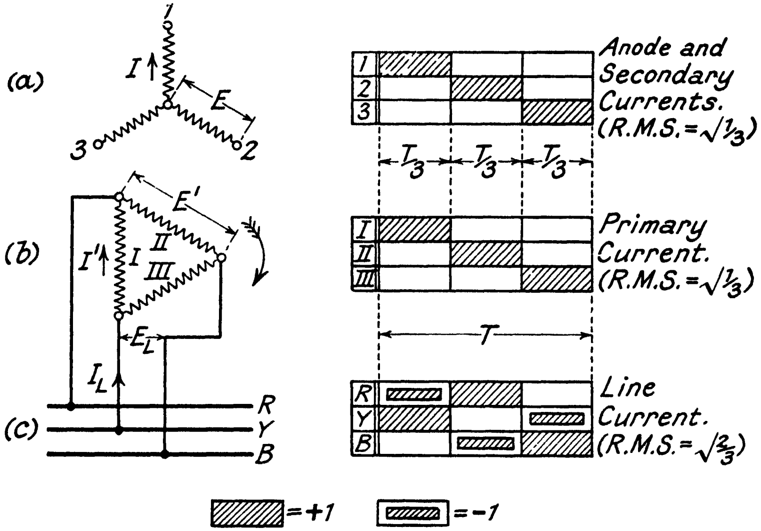
(a)
1
2
3
I
E
(b)
E'
I'
I
II
III
E_L
I_L
(c)
R
Y
B
1
2
3
Anode and Secondary Currents. (R.M.S.=√1/3)
T/3
T/3
T/3
I
II
III
Primary Current. (R.M.S.=√1/3)
T
R
Y
B
Line Current. (R.M.S.=√2/3)
=+1
=-1

FIG. 16. THREE-PHASE HALF-WAVE RECTIFICATION (STAR CONNECTION)

from the line, the current has to pass through the windings of the remaining two primary phases; and, as current can flow through only one secondary phase at a time, there are no corresponding secondary ampere-turns to balance the ampere-turns of these two primary phases. The consequent unbalancing results in a heavy unidirectional leakage flux that is detrimental to the voltage regulation of the rectifier unit.

In the case of three-phase rectification, with $p = 3$, the secondary phase voltage as given by equation (1) is

$$E = \frac{\pi}{3\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/3)} = 0{\cdot}855 V_{d_0} \quad . \quad . \quad . \quad . \quad (13a)$$

The distribution of the anode (and secondary) currents is given in Fig. 16 (*a*), from which it is seen that their r.m.s. value is

$$I = \sqrt{\frac{(1)^2}{3}} \,.\, I_d = 0{\cdot}577 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (13b)$$

The corresponding primary current distribution is shown in Fig. 16 (*b*). The ratio of primary to secondary phase current is E/E', so that the r.m.s. value of the primary current is

$$I' = \sqrt{\frac{(1)^2}{3}} \,.\, I_d \,.\, \frac{E}{E'} = 0{\cdot}577 I_d \,.\, \frac{E}{E'} \quad . \quad . \quad . \quad (13c)$$

The distribution of the line currents, shown in Fig. 15 (*c*), is obtained from a consideration of the primary currents. For instance, during the first third of the voltage cycle, when current flows through winding *I* of the delta primary, line *Y* supplies current (reckoned positive) to, whilst line *R* draws current (reckoned negative) from, this winding. From the diagram it is seen that the r.m.s. line current is therefore

$$I_L = \sqrt{\left[\frac{(-1)^2 + (1)^2}{3}\right]} \,.\, I_d \,.\, \frac{E}{E_L} = 0{\cdot}816 I_d \,.\, \frac{E}{E_L} \quad . \quad (13d)$$

Secondary Copper Loading. From Fig. 16 (*a*) it is seen that the kVA rating of the secondary winding is

$$W_2 = 3EI = 3 \times 0{\cdot}855 V_{d_0} \times 0{\cdot}577 I_d = 1{\cdot}48 W_d \quad . \quad (13e)$$

Primary Copper Loading. Similarly, from Fig. 16 (*b*), the kVA rating of the primary winding is seen to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}577 I_d \,.\, \frac{E}{E'} = 1{\cdot}48 W_d \quad . \quad . \quad (13f)$$

A.C. Supply Loading. Again, from Fig. 16 (*c*), the line kVA input is

$$W_L = (\sqrt{3})E_L I_L = (\sqrt{3})E_L \times 0{\cdot}816 I_d \,.\, \frac{E}{E_L} = 1{\cdot}21 W_d \,. \quad (13g)$$

Here also, as with single-phase rectification, the above current values and kVA ratings have to be corrected so as to allow for non-linearity of the output direct current. In the case of three-phase rectification (see page 38), it is necessary to multiply by the factor 1·016; so that the corrected figures are

$$I = 0{\cdot}587 I_d;\ I' = 0{\cdot}587 I_d \,.\, \frac{E}{E'};\ I_L = 0{\cdot}829 I_d \,.\, \frac{E}{E_L};$$

$$W_2 = 1{\cdot}505 W_d;\ W_1 = 1{\cdot}505 W_d;\ W_L = 1{\cdot}225 W_d \quad . \quad (13h)$$

The above simple three-phase rectifier circuit, although it is seldom used in practice because of the static magnetization of the transformer core to which it gives rise, presents several features of interest which become apparent on closer consideration of Fig. 16. In the first place, the currents flowing in the primary phases are seen to be blocks of direct current in exact antiphase with the corresponding secondary currents. This explains why the kVA ratings of both primary and secondary windings are the same. It also makes clear the fact that a star-connected primary winding cannot be employed. For such a connection requires that the algebraic sum of the individual phase currents shall be zero at every instant; and an examination of Fig. 16 (*b*) at once reveals that this condition is not satisfied. A further result of the asymmetrical form of the currents flowing in the primary phases of the rectifier transformer is that the line current has an r.m.s. value equal to $\sqrt{2}$ times the r.m.s. value of the primary current.

Three-phase Rectification (with Inter-star Connected Secondary). By making use of an inter-star connected secondary winding (Fig. 17), the unwanted feature of static magnetization of the core, associated with half-wave rectification of a three-phase alternating-current supply, is avoided, and each primary phase is made to carry a full cycle of current. This improved *modus operandi* effects an economy in copper on the primary side, which is, however, offset by the increased copper loading on the secondary side arising from the inter-star connection. As the result, the mean kVA rating of the rectifier transformer is reduced by only 2 per cent.

As before, with $p = 3$, the secondary phase voltage is

$$E = 0{\cdot}855 V_{d_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14a)$$

The distribution of the anode currents is given in Fig. 17 (*a*), from which it is seen that their r.m.s. value is

$$I_1 = \sqrt{\frac{(1)^2}{3}} \, . \, I_d = 0{\cdot}577 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (14b)$$

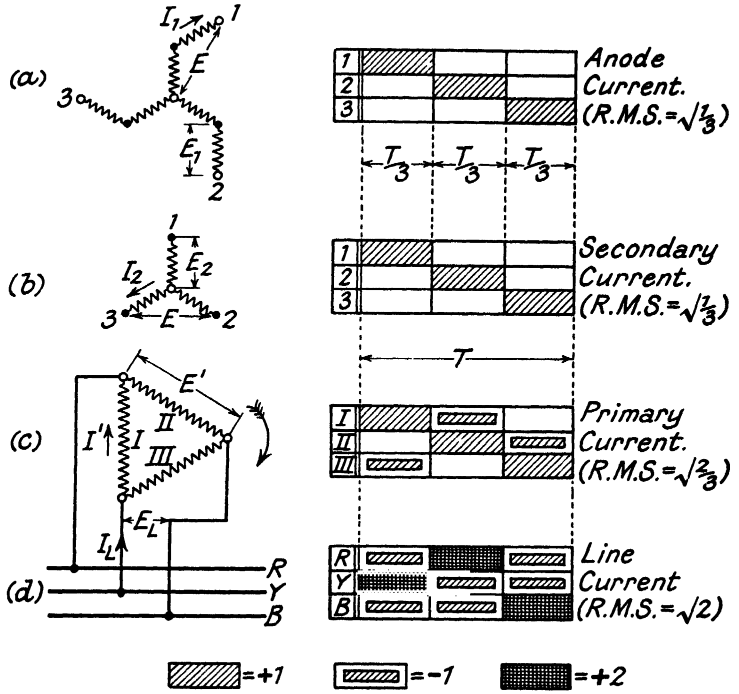
(a)
I_1
1
E
3
E_1
2
1
2
3
Anode Current. (R.M.S.=$\sqrt{1/3}$)
$T/3$
$T/3$
$T/3$
(b)
1
I_2
E_2
3
E
2
Secondary Current. (R.M.S.=$\sqrt{1/3}$)
T
(c)
E'
I'
I
II
III
Primary Current. (R.M.S.=$\sqrt{2/3}$)
E_L
I_L
(d)
R
Y
B
Line Current (R.M.S.=$\sqrt{2}$)
=+1
=−1
=+2

FIG. 17. THREE-PHASE HALF-WAVE RECTIFICATION (INTER-STAR CONNECTION)

The corresponding secondary current distribution is shown in Fig. 17 (*b*), giving an r.m.s. value

$$I_2 = \sqrt{\frac{(1)^2}{3}} \, . \, I_d = 0{\cdot}577 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (14c)$$

Due to the interconnection of the secondary phases, the primary ampere-turns required to balance the secondary ampere-turns due to the load current are always produced by currents flowing in *two* of the primary phases. Referring to Figs. 17 (*a*) and (*b*), when the load current is carried by anode 1, for example, the secondary ampere-turns due to the *anode* current are balanced by the primary ampere-turns produced by current flowing in the reverse direction in phase III of the primary winding; whilst, at the same instant, the corresponding secondary ampere-turns due to the *secondary* current are balanced by primary ampere-turns produced by current flowing in phase I of the primary winding. (In this case the anode and secondary currents are, of course, one and the same as their instantaneous values are identical and equal to the load current carried by the working anode; whilst both currents persist for the same duration of time, namely, one-third of a cycle.) The resulting primary current distribution is given in Fig. 17 (*c*). As the primary-to-secondary current ratio is $E_2/E' = E/(\sqrt{3})E'$, the r.m.s. value of the primary current is

$$I' = \sqrt{\left[\frac{(1)^2 + (-1)^2}{3}\right]} \,.\, I_d \,.\, \frac{E}{(\sqrt{3})E'} = 0{\cdot}471 I_d \,.\, \frac{E}{E'} \quad (14d)$$

The distribution of the line currents, shown in Fig. 17 (*d*), is obtained from a consideration of the primary currents. The current flowing in line R, for instance, is the difference of the currents in phases II and I. So that, taking the line currents in rotation, we may write

$$R = \text{II–I}; \; Y = \text{I–III}; \; B = \text{III–II}$$

From the diagram it is evident that the r.m.s. value of the line current is

$$I_L = \sqrt{\left[\frac{(-1)^2 + (2)^2 + (-1)^2}{3}\right]} \,.\, I_d \,.\, \frac{E_2}{E_L} = 1{\cdot}414 I_d \,.\, \frac{E_2}{E_L}$$

$$= 0{\cdot}816 I_d \,.\, \frac{E}{E_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14e)$$

Secondary Copper Loading. From Figs. 17 (*a*) and (*b*) it is seen that the kVA rating of the secondary winding is

$$W_2 = 3E_1I_1 + 3E_2I_2 = 6 \,.\, \frac{E}{\sqrt{3}} \,.\, 0{\cdot}577 I_d = 1{\cdot}71 W_d \,. \quad (14f)$$

Primary Copper Loading. Similarly, from Fig. 17 (*c*), the kVA rating of the primary winding is seen to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}471 I_d \,.\, \frac{E}{E'} = 1{\cdot}21 W_d. \quad . \quad (14g)$$

A.C. Supply Loading. Again, from Fig. 17 (*d*), the line kVA input is

$$W_L = (\sqrt{3})E_L I_L = (\sqrt{3})E_L \times 0{\cdot}816 I_d \,.\, \frac{E}{E_L} = 1{\cdot}21 W_d \,. \quad (14h)$$

As before, it is necessary to multiply by the factor 1·016 to correct the current values and kVA ratings for non-linearity of the output direct current; so that the corrected figures are

$$I_1 = I_2 = 0{\cdot}587 I_d;\ I' = 0{\cdot}48 I_d \,.\, \frac{E}{E'};\ I_L = 0{\cdot}829 I_d \,.\, \frac{E}{E_L};$$

$$W_2 = 1{\cdot}735 W_d;\ W_1 = 1{\cdot}225 W_d;\ W_L = 1{\cdot}225 W_d \quad . \quad (14i)$$

Referring to Fig. 17 (*c*), it is evident that at every instant the sum of the individual phase currents in the primary is zero. Hence a star-connected primary winding may be employed. And it will be found that its kVA rating is the same as that for the delta-connected winding considered above. Furthermore, as the result of the symmetry of the primary current wave-form obtained with inter-star connection of the secondary winding, the r.m.s. value of the line current is equal to $\sqrt{3}$ times that of the primary current—as is the case in an ordinary power transformer.

Four-phase (Two-phase Full-wave) Rectification. The full-wave or quarter-phase circuit represents the most efficient system of rectification in the case of a two-phase alternating current supply.* This circuit operates as a simple four-phase system, with $p = 4$, so that the secondary phase voltage, as given by equation (1), is

$$E = \frac{\pi}{4\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/4)} = 0{\cdot}785 V_{d_0} \quad . \quad . \quad . \quad . \quad (15a)$$

The anode (and secondary) current distribution is shown diagrammatically in Fig. 18 (*a*), from which

$$I = \sqrt{\frac{(1)^2}{4}} \,.\, I_d = 0{\cdot}5 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (15b)$$

---

* As mercury-arc rectifiers are generally provided with either 2, 3 or 6 anodes the possibility may arise of having to operate a six-anode rectifier, or two three-anode rectifiers from a two-phase supply. In such case the two-phase supply should be converted to a three-phase supply by means of a Scott-connected power transformer, and the rectifier equipment arranged for six-phase operation. Alternatively, a special two/six-phase connection should be adopted for the rectifier transformer, such as that given on p. 176 of *Mercury-Arc Power Rectifiers* by O. K. Marti and H. Winograd.

The corresponding primary current distribution is given in Fig. 18 (*b*). As the ratio of primary to secondary phase currents is E/E', the r.m.s. value of the primary current is

$$I' = \sqrt{\left[\frac{(1)^2 + (-1)^2}{4}\right]} \,.\, I_d \,.\, \frac{E}{E'} = 0{\cdot}707 I_d \,.\, \frac{E}{E'} \quad . \quad (15c)$$

From the diagram of Fig. 18 (*c*), giving the line current distribution, it is seen that the r.m.s. value is

$$I_L = \sqrt{\left[\frac{(-1)^2 + (1)^2}{4}\right]} \,.\, I_d \,.\, \frac{E}{E_L} = 0{\cdot}707 I_d \,.\, \frac{E}{E_L} \quad . \quad (15d)$$

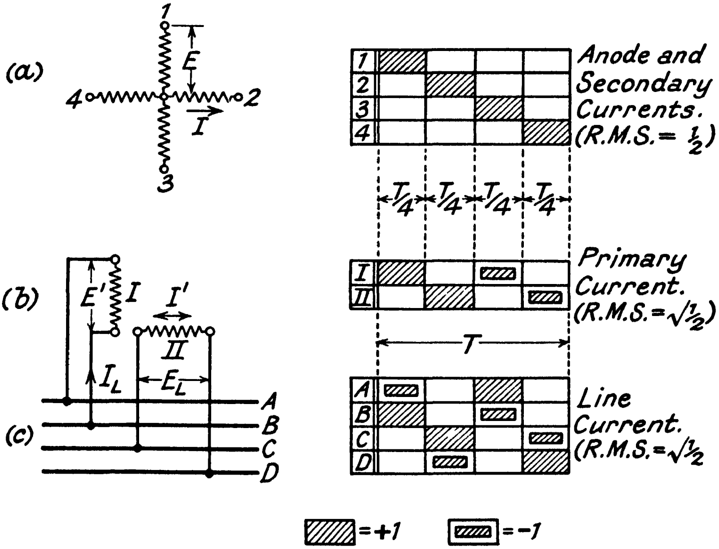

FIG. 18. TWO-PHASE FULL-WAVE RECTIFICATION

Secondary Copper Loading.

$$W_2 = 4EI = 4 \times 0{\cdot}785 V_{d,} \times 0{\cdot}5 I_d = 1{\cdot}57 W_d \quad . \quad (15e)$$

Primary Copper Loading.

$$W_1 = 2E'I' = 2E' \times 0{\cdot}707 I_d \,.\, \frac{E}{E'} = 1{\cdot}11 W_d. \quad . \quad (15f)$$

A.C. Supply Loading.

$$W_L = 2E_L I_L = 2E_L \times 0{\cdot}707 I_d \,.\, \frac{E}{E_L} = 1{\cdot}11 W_d \quad . \quad (15g)$$

CHAPTER V

RECTIFIER CIRCUIT THEORY (Contd.)

HAVING dealt with the more elementary types of transformer connections associated with two-phase, three-phase and four-phase operation of the mercury-arc rectifier, consideration must next be given to those circuits which are the most widely used in commercial rectifier installations. Pronounced harmonic ripple on the direct-current side, as well as poor power factor on the alternating-current side, both militate against three-phase working of the rectifier. Where a three-phase alternating-current supply is available, it is, therefore, general practice nowadays to adopt a method of transformer connection which enables the rectifier or rectifiers to operate on the six-phase system. In this way it is possible to obtain a fairly smooth direct-current output, in addition to comparative freedom from harmonics in the alternating-current supply.

Six-phase (Three-phase Full-wave) Rectification. The three-phase full-wave circuit (Fig. 19) represents the simplest transformer connection possible where six-phase rectification of a three-phase alternating-current supply is required. In spite of its simplicity, however, this connection presents certain undesirable features which tend to restrict its application. Although, and unlike the half-wave circuit from which it is developed, it does not give rise to static magnetization of the transformer core, yet it can only be employed with a delta-connected primary winding. With star-connection on the primary side, the mutual compensation of primary and secondary ampere-turns is incomplete; and the consequent unbalancing results in a residual m.m.f. which is, in this case, alternating and of triple frequency. Moreover, this residual m.m.f. is in phase on all three limbs of the transformer core and thus generates a triple-harmonic leakage flux which is sufficiently strong to induce current equalizing between pairs of rectifier phases—a phenomenon known as *phase equalizing*, and dealt with in a later section of this chapter. The effect of phase equalizing in this case is to split up the six-phase system into two three-phase systems in exact antiphase and with a common neutral point.

In the case of the simple six-phase rectifier circuit employing a star-connected secondary winding, we have $p = 6$, so that the secondary phase voltage as given by equation (1) is

$$E = \frac{\pi}{6\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/6)} = 0{\cdot}74 V_{d_0} \quad . \quad . \quad . \quad . \quad (16a)$$

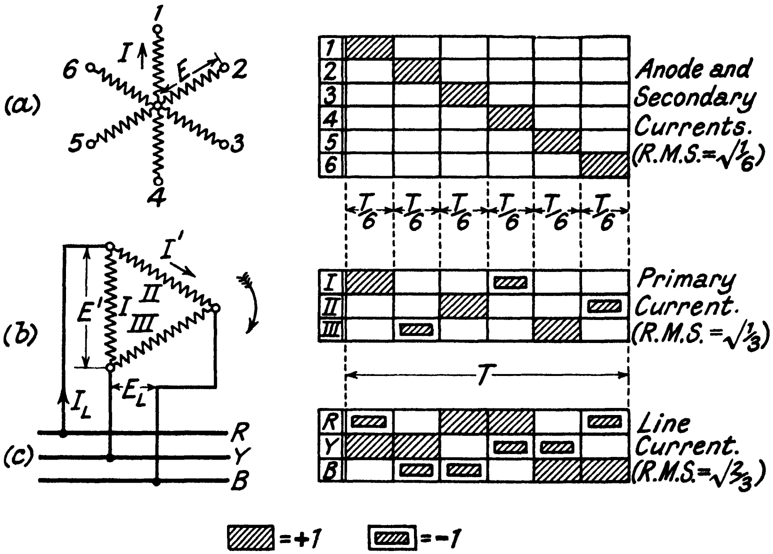
(a)
1
2
3
4
5
6
I
E
(b)
I'
E'
I
II
III
I_L
E_L
(c)
R
Y
B
1
2
3
4
5
6
Anode and Secondary Currents. (R.M.S.=√1/6)
T/6
T/6
T/6
T/6
T/6
T/6
I
II
III
Primary Current. (R.M.S.=√1/3)
T
R
Y
B
Line Current. (R.M.S.=√2/3)
=+1
=-1

FIG. 19. THREE-PHASE FULL-WAVE RECTIFICATION (STAR CONNECTION)

The distribution of the anode (and secondary) currents is given in Fig. 19 (*a*), from which it is seen that the r.m.s. value is

$$I = \sqrt{\frac{(1)^2}{6}} \, . \, I_d = 0{\cdot}408 I_d \quad . \quad . \quad . \quad . \quad . \quad (16b)$$

The corresponding primary current distribution is shown in Fig. 19 (*b*). The ratio of primary to secondary phase current is E/E', so that the r.m.s. value of the former is

$$I' = \sqrt{\left[\frac{(1)^2 + (-1)^2}{6}\right]} \, . \, I_d \, . \, \frac{E}{E'} = 0{\cdot}577 I_d \, . \, \frac{E}{E'} \quad . \quad (16c)$$

The distribution of the corresponding line currents, shown in Fig. 19 (*c*), is obtained by summation of the primary currents in phases II and I, I and III, and III and II, due regard being paid to algebraic sign as determined by the phase sequence and the direction of current flow. From the diagram it is seen that their r.m.s. value is

$$I_L = \sqrt{\left[\frac{(-1)^2 + (1)^2 + (1)^2 + (-1)^2}{6}\right]} \cdot I_d \cdot \frac{E}{E_L}$$

$$= 0{\cdot}816 I_d \cdot \frac{E}{E_L} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16d)$$

Secondary Copper Loading. From Fig. 19 (*a*) it is seen that the kVA rating of the secondary winding is

$$W_2 = 6EI = 6 \times 0{\cdot}74 V_{d_0} \times 0{\cdot}408 I_d = 1{\cdot}815 W_d \quad . \quad (16e)$$

Primary Copper Loading. Similarly, from Fig. 19 (*b*), the kVA rating of the primary winding is seen to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}577 I_d \cdot \frac{E}{E'} = 1{\cdot}285 W_d \quad . \quad (16f)$$

A.C. Supply Loading. Again, from Fig. 19 (*c*), it is seen that the line kVA input is

$$W_L = (\sqrt{3}) E_L I_L = (\sqrt{3}) E_L \times 0{\cdot}816 I_d \cdot \frac{E}{E_L} = 1{\cdot}05 W_d \ . (16g)$$

On comparing the above full-wave circuit with the corresponding half-wave circuit discussed in the last chapter, several points of interest are to be noted. In the first place the mean kVA rating of the transformer for six-phase operation is $1{\cdot}55 W_d$, as compared with $1{\cdot}51 W_d$ for three-phase working, so that on the score of economy alone one might tend to favour the simple three-phase rectifier circuit. But a consideration of the power factor of the rectifier transformer, that is, the ratio of the input kW to the input kVA, shows the corresponding values to be 0·95 and 0·81. Whilst taking the reduction in harmonic ripple on the direct-current side into account, indicated diagrammatically in Figs. 7 (*b*) and (*c*), the advantage in favour of six-phase operation is further evident.

In the second place a reference to Fig. 19 (*b*) indicates that, as in the case of the simple three-phase circuit, the algebraic sum of the primary phase currents at every instant in the voltage cycle is not equal to zero, so that a star-connected primary winding cannot be employed. In fact, in the same way that the primary current distribution given in Fig. 16 (*b*) indicates that with such a star-connection the residual m.m.f. is *unidirectional* in the case of the three-phase circuit, so Fig. 19 (*b*) shows that in the case of the six-phase circuit this residual m.m.f. is *alternating*; and that there are three successive magnetic cycles per voltage cycle, i.e. the alternating m.m.f. is of *triple frequency*.

A further result of this peculiar mode of operation of the rectifier transformer is that the line current has an r.m.s. value equal to $\sqrt{2}$ times the r.m.s. value of the current flowing in the delta-connected primary winding, as was found to be the case with the equivalent three-phase system of rectification.

The Six-phase Fork Circuit. The six-phase fork connection (Fig. 20)—or *triple-star* connection as it is sometimes called—is a development of the inter-star method of connection discussed in the last chapter, and results in an appreciable reduction in the mean kVA rating of the rectifier transformer. ~~Although in the three-phase case the reduction was only 2 per~~ cent, here, with six-phase rectification, the saving amounts to 8½ per cent.

As before, with $p = 6$, the secondary phase voltage is

$$E = 0{\cdot}74 V_{d_0} \qquad . \quad . \quad (17a)$$

The anode current distribution is given in Fig. 20 (*a*) from which

$$I_1 = \sqrt{\frac{(1)^2}{6}} \, . \, I_d = 0{\cdot}408 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (17b)$$

The corresponding secondary current distribution is shown in Fig. 20 (*b*). In this case each secondary phase (inner stretch) supplies two anodes in succession per voltage cycle, so that

$$I_2 = \sqrt{\left[\frac{(1)^2 + (1)^2}{6}\right]} \, . \, I_d = 0{\cdot}577 I_d \quad . \quad . \quad . \quad (17c)$$

In other words, the utilization factor of the inner stretches of the secondary winding is $\sqrt{2}$ times that of the outer stretches.

The phase voltage-ratio, primary to secondary, is $E'/E_1 = E'/E_2 = (\sqrt{3})E'/E$, so that the corresponding current ratio is $(1/\sqrt{3}) \, . \, (E/E')$. The primary current distribution, shown in Fig. 20 (*c*), is obtained by the summation of diagrams (*a*) and (*b*), having due regard to algebraic sign. Considering phase I, for example, the primary ampere-turns must balance the secondary ampere-turns due not only to the *anode* current (flowing in the outer stretches, 3 and 4) in the third and fourth phase-periods of the voltage cycle, but also to the *secondary* current (flowing in the inner stretch, 6–1) in the first and sixth phase periods. The latter are reckoned positive, whilst the former are reckoned negative. From diagram (*c*), therefore, the r.m.s. value of the primary phase currents is seen to be

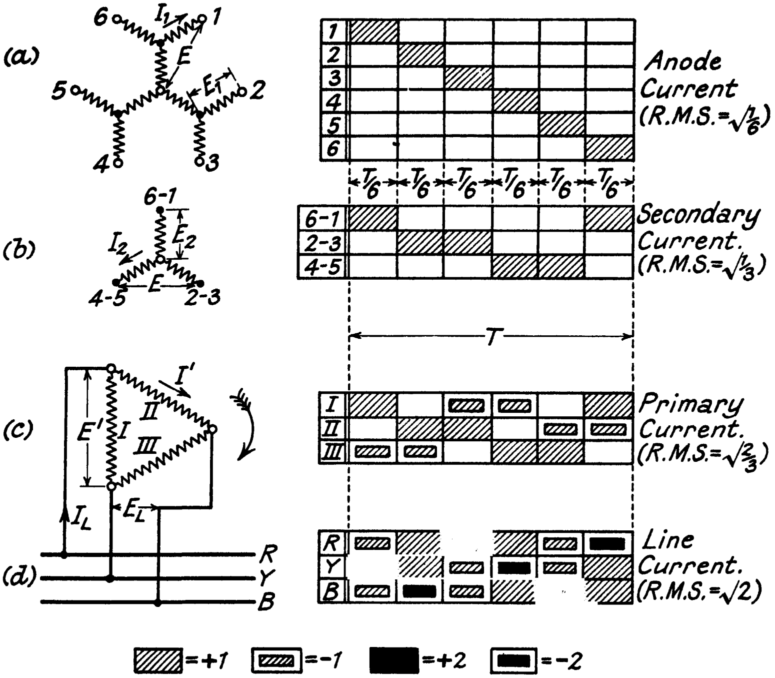
(a)
1
2
3
4
5
6
I_1
E
E_1
Anode Current (R.M.S.=$\sqrt{\frac{1}{6}}$)
$T/6$
(b)
6-1
2-3
4-5
I_2
E_2
E
Secondary Current. (R.M.S.=$\sqrt{\frac{1}{3}}$)
T
(c)
I'
E'
I
II
III
Primary Current. (R.M.S.=$\sqrt{\frac{2}{3}}$)
(d)
I_L
E_L
R
Y
B
Line Current. (R.M.S.=$\sqrt{2}$)
▨=+1
▭=−1
■=+2
▣=−2

FIG. 20. THREE-PHASE FULL-WAVE RECTIFICATION (FORK CONNECTION)

$$I' = \sqrt{\left[\frac{(1)^2 + (-1)^2 + (-1)^2 + (1)^2}{6}\right]} \cdot I_a \cdot \frac{1}{\sqrt{3}} \cdot \frac{E}{E'}$$

$$= 0{\cdot}471 I_a \cdot \frac{E}{E'} \qquad \ldots \qquad (17d)$$

The distribution of the line currents, given in Fig. 20 (*d*), is obtained by summation of the primary phase currents, due regard being again paid to algebraic sign as determined by the phase sequence and the direction of current flow. Taking the line currents in rotation, we may write them: $R = \mathrm{II} - \mathrm{I}$; $Y = \mathrm{I} - \mathrm{III}$; and $B = \mathrm{III} - \mathrm{II}$. From the diagram it is evident that their r.m.s. value is

$$I_L = \sqrt{\left[\frac{(-1)^2 + (1)^2 + (2)^2 + (1)^2 + (-1)^2 + (-2)^2}{6}\right]} \,.\, I_d \,.\, \frac{E_2}{E_L}$$

$$= (\sqrt{2}) I_d \,.\, \frac{1}{\sqrt{3}} \,.\, \frac{E}{E_L} = 0{\cdot}816 I_d \,.\, \frac{E}{E_L} \quad . \quad . \quad . \quad (17e)$$

Secondary Copper Loading. From Figs. 20 (*a*) and (*b*) we find for the kVA rating of the secondary winding

$$W_2 = 6E_1 I_1 + 3E_2 I_2 = \frac{3E}{\sqrt{3}}(2I_1 + I_2)$$

$$= \sqrt{3} \times 0{\cdot}74 V_{d_0} \times (0{\cdot}816 + 0{\cdot}577) I_d = 1{\cdot}79 W_d \quad (17f)$$

Primary Copper Loading. Similarly, from Fig. 20 (*c*), the kVA rating of the primary winding is found to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}471 I_d \,.\, \frac{E}{E'} = 1{\cdot}05 W_d. \quad . \quad (17g)$$

A.C. Supply Loading. Again, from Fig. 20 (*d*), the line input kVA is

$$W_L = (\sqrt{3}) E_L I_L = (\sqrt{3})\, E_L \times 0{\cdot}816 I_d \,.\, \frac{E}{E_L} = 1{\cdot}05 W_d \,. \quad (17h)$$

The mean kVA rating in the case of the fork connection is thus $1{\cdot}42 W_d$, as compared with $1{\cdot}55 W_d$ for the star connection —a reduction of 8½ per cent. At the same time it is seen that the algebraic sum of the individual phase currents in the primary is zero at every instant. A star-connected primary winding may therefore be employed instead of the delta-connected winding. Moreover, it will be found that the kVA rating is the same, as is also the line input kVA. As a further result of the symmetry of the primary current wave-form obtained with a fork-connected secondary, the r.m.s. value of the line current is equal to $\sqrt{3}$ times that of the primary current—as is the case with a normal power transformer.

Phase-equalizing Circuits. Up to the present we have considered only methods of rectification in which, apart from the brief interval of overlap during which the current arc commutates from one anode to the next, only one anode at a time carries the full direct current delivered by the rectifier. But the poor utilization of the rectifier phases associated with simple rectifier circuits of this type of necessity leads to large and uneconomic transformers, and is therefore a disadvantage to be reckoned with in spite of the comparative freedom from harmonic ripple in the direct-current output which is characteristic of six-phase and, in particular, of twelve-phase rectifier systems.

Rectifier circuits have consequently been developed which operate so that two, three, or even four anodes carry current simultaneously, and during a considerably greater portion of the voltage cycle than that obtaining in the case of simple multiple-phase rectifier circuits. Such systems function by means of what is called *phase equalizing*; that is, a process by which either successive phases or independent phase-groups are electro-magnetically coupled so as to produce anode voltages which are more or less trapezoidal in wave-form, corresponding to the combined sinusoidal voltages of the simultaneously operating phases. Rectifier circuits employing phase equalizing are thus characterized by the features that as many anodes carry current simultaneously as there are couplings between phases or phase-groups; and that the output voltage at any instant is equal to the mean of the voltages of the simultaneously working phases.

By means of phase equalizing, then, the advantage of reasonably smooth output voltage resulting from phase multiplication is obtained without the concomitant disadvantage of poor utility factor. By far the most convenient way of applying the phase-equalizing principle to a multiple-phase system consists in subdividing it into two or more independent systems of similar and symmetrical phase-groups, having each a value of p which is a submultiple of the total number of rectifier phases, and arranged so as to be displaced in phase with respect to one another. The neutral points of these phase-groups are then joined to the negative pole of the direct-current system through one or more special choke coils—known as *phase equalizers*—which are magnetized by the harmonic currents flowing in the individual secondary windings of the rectifier transformer, and which thus produce the corresponding harmonic voltages necessary to equalize the instantaneous voltage difference between simultaneously operating phases. The phase equalizers also ensure that the direct current is divided equally between the several phase-groups, and that it is at all instants carried equally by certain phases, one from each group, working together and in rotation.

In the case of rectifier systems having a six-phase character, the most commonly employed arrangement of this type is the double three-phase connection with two-core phase equalizer.* In this arrangement the six-phase system is subdivided into two independent three-phase systems displaced in phase by 180 electrical degrees, and made to operate in parallel by means of the phase equalizer connected between their neutral points. The voltage conditions obtaining in this case are illustrated by Fig. 21 (*b*), from which it is seen that the triple-frequency ripples in the output voltages of the two systems combine to produce a much smaller ripple of sextuple frequency, as is the case with simple six-phase rectification shown in Fig. 21 (*a*). The load current is shared equally between the two three-phase systems, which operate in parallel at a terminal voltage intermediate between the potentials of the two phase-groups. Each phase-group operates as a simple three-phase rectifier system; at the same time the rectifier circuit as a whole possesses a six-phase character. It is seen that the output voltage V_{d_0} is that corresponding to three-phase operation and, for the same r.m.s. phase voltage E, is thus 13 per cent lower than in the case of simple six-phase working.

The two windings of the phase equalizer are invariably arranged on the core in such a way that the direct currents flowing in them magnetize the core in opposite senses. As these currents are equal—each being half the total direct current delivered by the rectifier—their m.m.f.s balance, and do not produce any magnetization of the core. The core is magnetized only by a third-harmonic current which circulates between the neutral points of the three-phase systems and produces a corresponding third-harmonic flux which, in turn, generates the required phase-equalizing voltage. This circulating current

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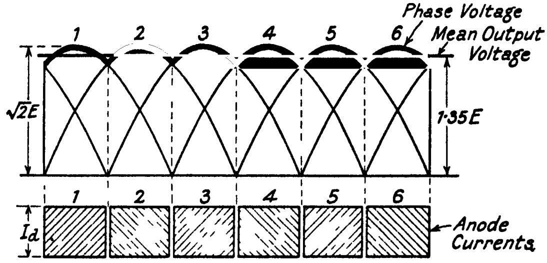
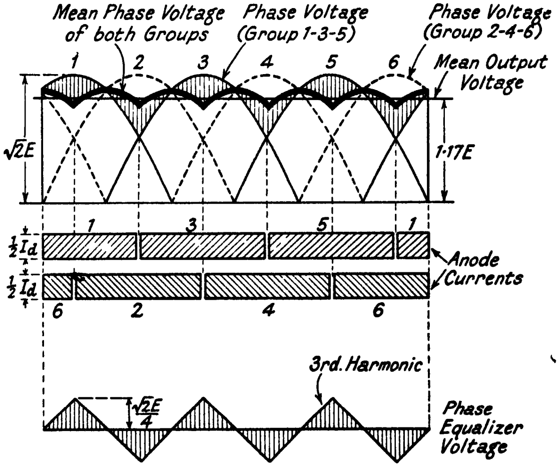
* Generally referred to as an *absorption reactance coil*, although the term *interphase transformer* is also frequently used to describe this type of phase-equalizing device. In the author's view the latter term ought to be applied only to those phase-equalizing devices which directly couple adjacent phases of a multiple-phase rectifier system, and which thus do not involve the necessity of splitting up the system into several independent phase-groups. An example of this type of device is the so-called "current divider" (*Stromteiler*) employed by Messrs. Siemens-Schuckert-Werke A.G., and connected between the secondary terminals of the rectifier transformer and the anodes of the rectifier.



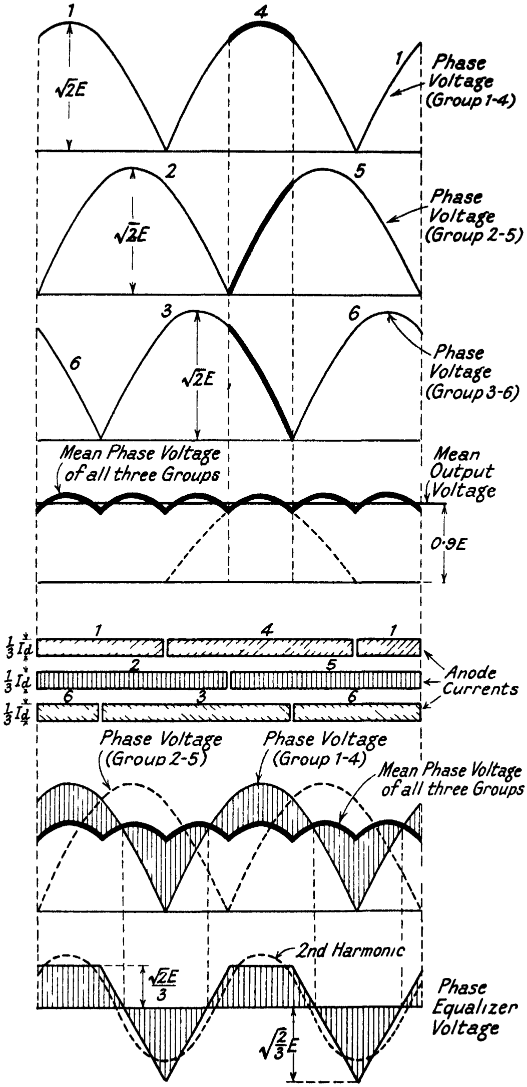
(a) Six-phase rectification



(b) Double three-phase rectification

FIG. 21. VOLTAGE AND CURRENT RELATIONS IN PHASE-EQUALIZING CIRCUITS

originates from the third-harmonic component inherent in the anode-current rectangles pertaining to six-phase rectifier operation (see Table), and which are absent in the case of three-phase working. The triple-harmonic flux is thus actually generated by the difference between the two blocks of direct current—the anode currents corresponding to the two


1
4
1
√2E
Phase Voltage (Group 1-4)
2
5
√2E
Phase Voltage (Group 2-5)
3
6
6
√2E
Phase Voltage (Group 3-6)
Mean Phase Voltage of all three Groups
Mean Output Voltage
0·9E
1/3 Id
1
4
1
2
5
6
3
6
Anode Currents
Phase Voltage (Group 2-5)
Phase Voltage (Group 1-4)
Mean Phase Voltage of all three Groups
2nd Harmonic
√2E/3
√(2/3)E
Phase Equalizer Voltage

(c) Triple single-phase rectification

FIG. 21. VOLTAGE AND CURRENT RELATIONS IN PHASE-EQUALIZING CIRCUITS

simultaneously operating phases, in other words—which at any instant flow in the windings of the phase equalizer.*

The phase equalizer accordingly functions simply by "absorbing" the third harmonic contained in successive pairs of simultaneously flowing anode currents, and utilizing it to generate a triple-frequency voltage which equalizes the instantaneous potential difference between the two three-phase systems—hence the origin of the term "absorption reactance coil."

A little consideration will show that if the load on the rectifier falls below a certain minimum value—known as the *critical* or *transition load*, and having a value which is generally less than 1 per cent of full load—then the instantaneous difference in magnitude between the direct currents flowing in the two windings of the phase equalizer is insufficient to generate the required triple-frequency flux, with the result that the phase equalizer ceases to function in the above manner. Instead, it acts merely as a short-circuit connection between the neutral points of the two three-phase systems. The rectifier circuit then reverts to a simple six-phase system, and the output voltage V_{d_0} rises from the value $1{\cdot}17E$ to the value $1{\cdot}35E$—a rise of 15 per cent.

This sudden rise of voltage in the no-load region is a characteristic feature of all phase-equalizing circuits; and in cases where there are practical objections to it, recourse must be had to special means of supplying a harmonic-frequency magnetizing current to the phase equalizer from some external source whenever the rectifier load falls below the critical value.

From a practical point of view the phase equalizer is nothing other than a single-phase boosting transformer with a : 1 voltage ratio. The voltage across each of its two windings, being the difference between the mean potentials of both phase-groups and the phase voltage of one three-phase system, has a nearly triangular wave-form as shown in the lower diagram of Fig. 21 (*b*). Its amplitude is equal to $\frac{1}{4}(\sqrt{2})E$, and its r.m.s. value is thus approximately $\frac{1}{4}V_{d_0}$. Looking upon the phase equalizer as a normal two-winding transformer operating at the frequency of the alternating-current supply, and bearing in mind that the voltage per winding is inversely proportional to the magnetic frequency, it is seen that the equivalent kVA rating is

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* For a fuller treatment of the *modus operandi* of the phase equalizer the reader is referred to a paper by H. Jungmichl entitled: "The Phase Equalizer in Heavy-Duty Rectifier Installations," and published in *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1928, Vol. 6, pp. 34–57 (Julius Springer, Berlin). This paper is in its way a classic. It deals with the principles of phase equalizing in a manner that is both thorough and methodical, and which is at the same time sufficiently lucid to be of interest to the inquiring student.

$$2 \times \tfrac{1}{3} \cdot \frac{V_{d_0}}{4} \times \frac{I_d}{2} = \tfrac{1}{12} W_d,$$

that is, 8½ per cent of the kW input to the rectifier.

The double three-phase circuit has the great merit of simplicity and, as will be shown later, ~~it has the further~~ advantage of providing the best overall utilization of the rectifier transformer which it is possible ~~to achieve with six-phase~~ rectification. For these reasons it is probably the most widely used circuit in rectifier practice at the present time.

~~An alternative~~ arrangement of phase-equalizing circuit which, by reducing the crest factor of the anode currents still further, gives an even lower specific current loading of the rectifier anodes—a feature of very great practical importance—is the triple single-phase circuit with three-core phase equalizer. In this arrangement the six-phase rectifier system is subdivided into three independent phase-groups having a single-phase (full-wave) character, and displaced in phase from one another by 120 electrical degrees. These single-phase systems are then made to operate in parallel by means of the three windings of the phase equalizer connected between their neutral points and the negative pole of the direct-current system. The voltage conditions arising in this case are depicted in Fig. 21 (*c*), from which it is seen that the heavy double-frequency pulsations in the output voltage waves of the three systems combine to produce the very moderate voltage ripple characteristic of six-phase working, and illustrated in Fig. 21 (*a*). The load current is shared equally between the single-phase systems, which operate in parallel at a terminal voltage that is the average of the potentials of the three phase-groups. Each phase-group operates as a single-phase full-wave rectifier system; whilst, on the other hand, the rectifier circuit as a whole possesses six-phase character. As shown by the upper diagrams of Fig. 21 (*c*), the mean output voltage V_{d_0} is accordingly that corresponding to $p = 2$ and, for the same r.m.s. phase voltage E, is thus 33 per cent lower than in the case of simple six-phase working.

In this system the phase equalizer is arranged as a three-phase iron-cored choke coil, each of the three windings carrying one-third of the total direct current delivered by the rectifier. The voltage across each winding, being the difference between the mean potential of the three phase-groups and the phase voltage of any one of them, has a principal frequency which is twice that of the alternating-current supply. As shown by the lower diagrams of Fig. 21 (*c*), this voltage is unsymmetrical and thus contains even harmonics of still higher frequency. Its r.m.s. value is approximately $\frac{1}{2}V_{d_0}$; so that looking upon the phase equalizer as a normal three-winding auto-transformer operating at the frequency of the alternating-current supply, its equivalent kVA rating is

$$3 \times \tfrac{1}{2} \cdot \frac{V_{d_0}}{2} \times \frac{I_d}{3} = \tfrac{1}{4} \cdot W_d$$

that is, 25 per cent of the kW input to the rectifier.

With triple single-phase rectification, therefore, the phase equalizer is three times as large as with double three-phase rectification; furthermore, it has three cores and windings instead of two, and it thus costs still more. This fact, together with a slightly lower overall utilization of the transformer as compared with the double three-phase arrangement, explains why the triple single-phase rectifier circuit has found but little application in practice.

Further examples of phase-equalizing circuits are those possessing twelve-phase character, such as (1) the quadruple three-phase circuit with three two-core phase equalizers, (2) the triple four-phase circuit with three-core phase equalizer, and (3) the double six-phase circuit with two-core phase equalizer. These will be dealt with in the next chapter.

The Double Three-phase Circuit. As already mentioned, the double three-phase circuit (Fig. 22) represents the simplest phase-equalizing arrangement which can be applied to six-phase rectification. In this case each half of the six-phase system operates on the three-phase principle, so that $p = 3$, and the secondary phase voltage is consequently

$$E = \frac{\pi}{3\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/3)} = 0{\cdot}855 V_{d_0} \quad . \quad . \quad . \quad . \quad (18a)$$

The distribution of anode (and secondary) currents is given in Fig. 22 (*a*). It is seen that each anode carries half the total direct current I_d during one-third of the voltage cycle, i.e. over 120 electrical degrees; and that two anodes, one from each phase-group, are always in operation together at any instant. Hence the r.m.s. value of the anode current is

$$I = \sqrt{\left[\frac{(1)^2 + (1)^2}{6}\right]} \cdot \frac{I_d}{2} = \frac{1}{2}\left(\sqrt{\frac{1}{3}}\right) I_d = 0{\cdot}289 I_d \quad . \quad (18b)$$

The corresponding primary current distribution is given in Fig. 22 (*b*); and as the phase-current ratio, primary to secondary, is E/E', the r.m.s. primary current is

$$I' = \sqrt{\left[\frac{(1)^2 + (1)^2 + (-1)^2 + (-1)^2}{6}\right]} \cdot \frac{I_d}{2} \cdot \frac{E}{E'}$$

$$= \frac{1}{2}\left(\sqrt{\frac{2}{3}}\right) I_d \cdot \frac{E}{E'} = 0{\cdot}408 I_d \cdot \frac{E}{E'} \quad . \quad . \quad . \quad (18c)$$

The distribution of the line currents, shown in Fig. 22 (*c*), is obtained in the usual way from a consideration of the primary currents. Taking the line currents in rotation, we may write

$$R = \text{II} - \text{I}; \; Y = \text{I} - \text{III}; \; B = \text{III} - \text{II}$$

From the diagram it is evident that their r.m.s. value is

$$I_L = \sqrt{\left[\frac{(-2)^2 + (-1)^2 + (1)^2 + (2)^2 + (1)^2 + (-1)^2}{6}\right]} \cdot \frac{I_d}{2} \cdot \frac{E}{E_L}$$

$$= \frac{1}{2}(\sqrt{2}) I_d \cdot \frac{E}{E_L} = 0{\cdot}707 I_d \cdot \frac{E}{E_L} \quad . \quad . \quad . \quad . \quad (18d)$$

Secondary Copper Loading. From Fig. 22 (*a*) it is seen that the kVA rating of the secondary winding is

$$W_2 = 6EI = 6 \times 0{\cdot}855 V_{d_0} \times 0{\cdot}289 I_d = 1{\cdot}48 W_d \quad . \quad (18e)$$

Primary Copper Loading. Similarly, from Fig. 22 (*b*) the kVA rating of the primary winding is seen to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}408 I_d \cdot \frac{E}{E'} = 1{\cdot}05 W_d. \quad . \quad (18f)$$

A.C. Supply Loading. Again, from Fig. 22 (*c*), the line input kVA is equal to

$$W_L = (\sqrt{3}) E_L I_L = (\sqrt{3}) E_L \times 0{\cdot}207 I_d \cdot \frac{E}{E_L} = 1{\cdot}05 W_d \quad (18g)$$

Referring to Fig. 22 (*b*), it is evident that at every instant the sum of the individual phase currents in the primary winding is zero, so that a star-connected primary winding may be employed. Moreover, it will be found that its kVA rating is exactly the same as that for the delta-connected winding considered above. Here again, as the result of the symmetry of the primary current wave-form, the r.m.s. value of the line current is equal to $\sqrt{3}$ times that of the primary current, in the case of the delta-connected winding.

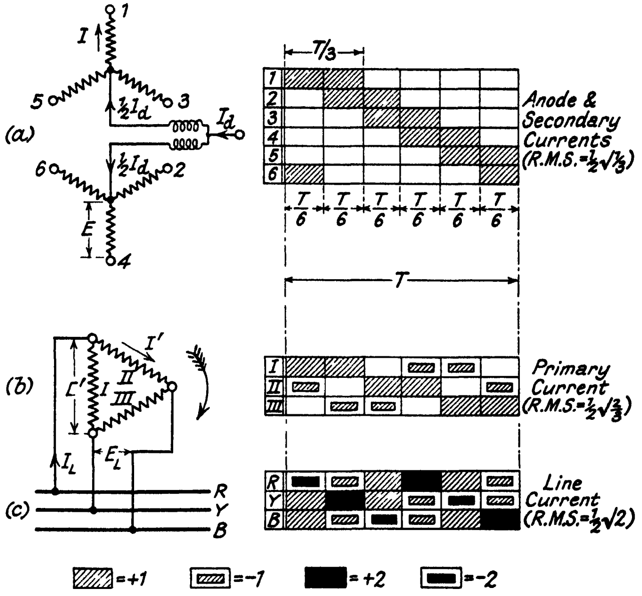
(a)
1
I
5
3
½I_d
I_d
6
2
E
4
T/3
1
2
3
4
5
6
Anode & Secondary Currents (R.M.S.=½√⅓)
T/6
T
(b)
I′
E′
I
II
III
I_L
E_L
Primary Current (R.M.S.=½√⅔)
(c)
R
Y
B
Line Current (R.M.S.=½√2)
▨=+1
=−1
■=+2
=−2

FIG. 22. DOUBLE-THREE-PHASE RECTIFICATION

In the previous section the equivalent kVA rating of the phase equalizer was shown to be $0{\cdot}083 W_d$. The mean kVA rating of the transformer unit as a whole is therefore $1{\cdot}35 W_d$, which figure represents a reduction of 5 per cent as compared with the six-phase fork connection, and of no less than 13 per cent as compared with simple six-phase rectification. At the same time, the specific anode loading is reduced in the ratio of 0·289 to 0·408, that is, by 30 per cent. For these reasons the double three-phase method of connection is nearly always adopted for six-phase rectifiers.

The Triple Single-phase Circuit. An alternative phase-equalizing arrangement which can be applied to a six-phase rectifier system is that shown in Fig. 23. Here each of three single-phase groups carries one-third of the total direct current delivered by the rectifier system. As each phase-group operates as a single-phase full-wave rectifier system, with $p = 2$, the secondary phase voltage is given by

$$E = \frac{\pi}{2\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/2)} = 1{\cdot}11 V_{d_0} \quad . \quad . \quad . \quad . \quad (19a)$$

The distribution of the anode (and secondary) currents is shown in Fig. 23 (*a*), from which it is seen that each anode carries current during one-half of the voltage cycle, i.e. over 180 electrical degrees; and that altogether three anodes, one from each phase-group, share the total direct current I_d equally between them at any instant. Hence the r.m.s. value of the anode current is

$$I = \sqrt{\left[\frac{(1)^2 + (1)^2 + (1)^2}{6}\right]} \cdot \frac{I_d}{3} = \frac{1}{3}\left(\sqrt{\frac{1}{2}}\right) \cdot I_d$$

$$= 0{\cdot}236 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19b)$$

The corresponding primary current distribution is shown in Fig. 23 (*b*); and as the ratio of primary to secondary phase current is E/E', the r.m.s. value of the primary current is

$$I' = \sqrt{\left[\frac{(1)^2 + (1)^2 + (1)^2 + (-1)^2 + (-1)^2 + (-1)^2}{6}\right]} \cdot \frac{Id}{3} \cdot \frac{E}{E'}$$

$$= 0{\cdot}333 I_d \cdot \frac{E}{E'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19c)$$

From the diagram of Fig. 23 (*c*), the r.m.s. value of the line current is seen to be

$$I_L = \sqrt{\left[\frac{(2)^2 + (2)^2 + (-2)^2 + (-2)^2}{6}\right]} \cdot \frac{I_d}{3} \cdot \frac{E}{E_L}$$

$$= \frac{2}{3}\left(\sqrt{\frac{2}{3}}\right) I_d \cdot \frac{E}{E_L} = 0{\cdot}544 I_d \cdot \frac{E}{E_L} \quad . \quad . \quad . \quad (19d)$$

Secondary Copper Loading. From Fig. 23 (*a*) we obtain

$$W_2 = 6EI = 6 \times 1{\cdot}11 V_{d_0} \times 0{\cdot}236 I_d = 1{\cdot}57 W_d \quad . \quad (19e)$$

Primary Copper Loading. Similarly, from Fig. 23 (*b*) we have

$$W_1 = 3E'I' = 3E' \times 0{\cdot}333I_d \cdot \frac{E}{E'} = 1{\cdot}11W_d \quad . \quad (19f)$$

A.C. Supply Loading. From Fig. 23 (*c*), the line input kVA is

$$W_L = (\sqrt{3})E_LI_L = (\sqrt{3})E_L \times 0{\cdot}544I_d \cdot \frac{E}{E_L} = 1{\cdot}05W_d \ . \ (19g)$$

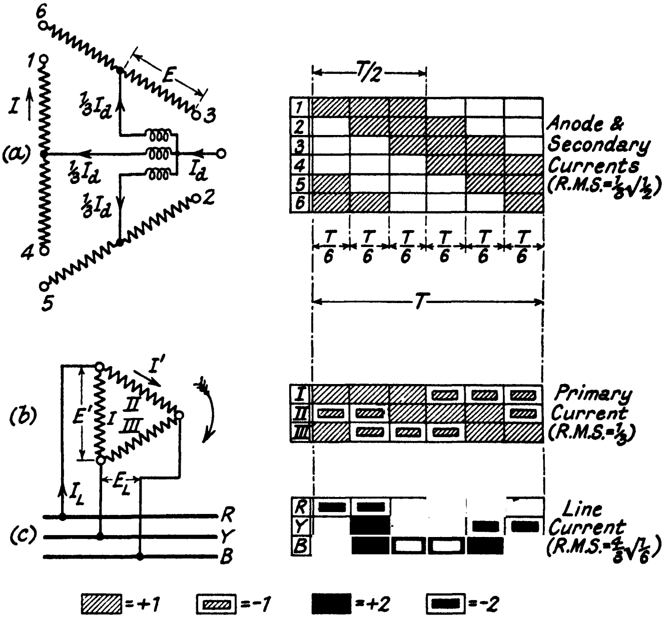
6
1
I
(a)
4
5
E
3
2
⅓I_d
I_d
T/2
1
2
3
4
5
6
Anode & Secondary Currents (R.M.S.=⅓√½)
T/6
T
(b)
E'
I
II
III
I'
Primary Current (R.M.S.=⅓)
(c)
I_L
E_L
R
Y
B
Line Current (R.M.S.=4/3√⅙)
▨=+1
▭=−1
■=+2
▣=−2

FIG. 23. TRIPLE SINGLE-PHASE RECTIFICATION

Referring to Fig. 23 (*b*), it is seen that a star-connected primary winding cannot be employed, because the algebraic sum of the individual phase currents is not equal to zero at every instant. This is confirmed by the fact that the ratio between the line and primary currents is not $\sqrt{3} : 1$.

It has been shown previously that the equivalent kVA rating of the three-core phase equalizer, which is a necessary operating feature of this particular circuit, is $0{\cdot}25W_d$. Hence the mean kVA rating of the transformer unit as a whole is $1{\cdot}59W_d$, which represents an increase of 2½ per cent as compared even with the simple six-phase delta/star connection, and of 12 per cent as compared with the six-phase fork connection; and compared with the double three-phase connection, the increase in rating is as much as 18 per cent. For this reason the triple single-phase method of phase equalizing is scarcely employed at all, except in cases where the advantage to be gained from the greatly reduced specific anode loading is of practical importance. In this case the reduction is in the ratio of 0·236 to 0·289, representing an amount of 18 per cent. For example, a six-anode glass-bulb rectifier having anodes individually capable of carrying 100 r.m.s. amperes continuously without overheating, can only deliver a direct-current output of 350 A when supplied from a transformer with a double three-phase secondary winding; but the same rectifier can be made to deliver 425 A continuously when supplied from a somewhat larger transformer having a triple single-phase secondary winding.

CHAPTER VI

RECTIFIER CIRCUIT THEORY (Contd.)

THE preceding chapter was devoted to those methods of transformer connection giving the rectifier circuit a six-phase character, both as regards "smoothness" of the direct-current output from the rectifier and with respect to harmonic distortion of the alternating-current input to the rectifier transformer. In the present chapter we shall consider certain types of rectifier circuit in which the process of phase multiplication is carried still further, so that the disturbing effects of the harmonics generated by the rectifier are practically negligible.

Twelve-phase Rectification. The advantages, then, of the twelve-phase system of rectifier operation are twofold. In the first place, the output voltage is almost rectilinear, even in the case of a pure resistance load where the individual anode currents are no longer rectangles, but the centre sections of sinusoidal half-waves. Referring to Fig. 7 (*c*), for example, it can be shown that the maximum deviation of the output voltage wave-form from the pure direct form amounts to approximately 6 per cent in the case of six-phase operation; whilst this deviation is reduced to a mere 1½ per cent when recourse is had to twelve-phase operation. In the second place, the current drawn by the rectifier unit from the alternating-current supply is practically sinusoidal. This feature is dealt with more fully in Chapter XIV. Suffice it to say here that, whereas in the case of six-phase operation the distortion factor* of the input current is 0·95, it becomes 0·99 in the case of twelve-phase rectification.

The main disadvantage of the twelve-phase system of rectifier operation is the poor utility factor of the transformer, a feature which is evident from a consideration of equation (3). For example, the utility factor of the rectifier phases in the case of a simple six-phase system is 0·552, which already represents a reduction of 18 per cent below the maximum possible value of 0·675 obtained with $p = 3$; and in the case of a simple twelve-phase system this utility factor is only 0·404, representing a reduction of no less than 40 per cent below the maximum attainable.

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* The ratio between the r.m.s. values of the fundamental component and the total line current. (Cf. Chapter XIV.)

Another serious drawback of the twelve-phase system is the complicated nature of the transformer windings. To obtain twelve secondary voltage vectors, displaced in phase by 30 electrical degrees, from a three-phase alternating-current supply it is necessary to combine two or more windings of a basically three-phase secondary system, at any rate if use is to be made of conventional three-core types of transformer. The constructional difficulties involved are naturally much greater than in the case of the six-phase fork connection discussed in the last chapter. But here also they are to a certain extent offset by an improvement in the utility factor of the transformer as a whole resulting from such methods of phase-combination.

In the author's experience there is little to be said in favour of simple twelve-phase operation of the mercury-arc rectifier. It is true that many ingenious methods of phase-combination have from time to time been devised with the object of procuring a twelve-phase secondary connection for the rectifier transformer. But the majority of these connections become unstable with load and eventually lose their twelve-phase character, either through multiplicity of the secondary windings or by reason of inherent asymmetry of the connection. Split-phase, composite double-star, or double-fork, as well as certain semi-polygonal connections are essentially asymmetrical. In the case of simple fork and polygon connections, on the other hand, the distribution of reactance is to all intents and purposes symmetrical, so that these would be expected to retain their twelve-phase character under all conditions of loading. At the same time, all of the foregoing types of transformer connection have one drawback in common. With simple twelve-phase operation of the rectifier, the voltage difference between successive phases during the working period becomes so small that the current arc frequently misses a phase, resulting in a tendency towards instability of the output voltage and possible reversion to a six-phase operation.

In view of the costly design and the many constructional difficulties encountered in such twelve-phase transformers, it is very difficult to see any real justification, other than that of comparative freedom from harmonics on the input side, for any departure from standard six-phase practice. As already mentioned, the residual harmonics on the alternating-current side are of relatively small magnitude, and hence the line current is practically sinusoidal; and it is this feature of the twelve-phase rectifier, more than any other, which renders it superior to the six-phase rectifier. Thus it is only where the cumulative effect of the harmonics taken by the rectifier from the alternating-current supply makes itself felt, e.g. in the case of an extensive direct-current traction system fed solely from rectifier substations, that serious consideration may have to be given to twelve-phase working.

The Twelve-phase Fork Circuit. The twelve-phase fork circuit (Fig. 24) is a development of the six-phase fork circuit discussed in the previous chapter, and represents the most economical method of phase-combination possible where simple twelve-phase rectification of a three-phase alternating-current supply is required. With this type of connection, then, each rectifier phase carries the full direct current during one-twelfth of a cycle, i.e. over 30 electrical degrees. Apart from poor utility factor arising from such a short period of current loading per phase, the twelve-phase fork connection has the disadvantage that it can only be employed with a delta-connected primary winding. With star connection on the primary side, the balancing of secondary and primary ampere-turns is incomplete, resulting in a residual m.m.f. which is alternating and of triple frequency, as in the case of the simple six-phase circuit.

Referring to the diagram of Fig. 24 (*a*), it is seen that the individual phase voltages E are obtained by combination of the voltages E_1 and E_2 across the outer and inner stretches of the secondary windings arranged on the three limbs of the transformer core; and that the relation between these several voltages is given by

$$\frac{E}{\sin 120^\circ} = \frac{E_1}{\sin 15^\circ} = \frac{E_2}{\sin 45^\circ}$$

from which

$$E_1 = \frac{E \,.\, \sin 15^\circ}{\sin 120^\circ} = \frac{E(\sqrt{3} - 1)}{2\sqrt{2}} \cdot \frac{2}{\sqrt{3}} = 0{\cdot}298E \quad . \quad (20a)$$

and

$$E_2 = \frac{E \,.\, \sin 45^\circ}{\sin 120^\circ} = \frac{E}{\sqrt{2}} \cdot \frac{2}{\sqrt{3}} = 0{\cdot}816E \quad . \quad . \quad (20b)$$

In the case of simple twelve-phase rectification, with $p = 12$, the secondary phase voltage as given by equation (1) is

$$E = \frac{\pi}{12\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/12)} = 0{\cdot}715 V_{d_0} \quad . \quad . \quad . \quad (20c)$$

The distribution of the anode currents is given in Fig. 24(a), from which the r.m.s. value is seen to be

$$I_1 = \sqrt{\frac{(1)^2}{12}} \, . \, I_d = 0{\cdot}289 I_d \quad . \quad . \quad (20d)$$

The corresponding secondary current distribution is shown in Fig. 24 (b). As in the case of the six-phase fork connection, each secondary phase (inner stretch) supplies two anodes in succession per voltage cycle, so that the r.m.s. secondary current is

$$I_2 = \sqrt{\left[\frac{(1)^2 + (1)^2}{12}\right]} I_d = 0{\cdot}408 I_d \, . \quad . \quad (20e)$$

The distribution of the corresponding primary currents, illustrated in Fig. 24 (c), is obtained from diagrams (a) and (b) as follows.

Consider first of all the outer stretches of the secondary winding. If the primary and secondary ampere-turns are to be balanced, then the current relation between primary and secondary must be inversely proportional to the number of turns, and hence equal to $E_1/E' = 0{\cdot}298 E/E'$. Similarly, considering the inner stretches of the secondary winding, the corresponding ratio of instantaneous primary to secondary current is equal to $E_2/E' = 0{\cdot}816 E/E'$. Diagram ($c$) is then obtained in the usual way by summation of the instantaneous currents given in diagrams (a) and (b), due regard being paid to algebraic sign as determined by the phase sequence, and taking into account the above current ratios.

For instance, during the first twelfth of the voltage cycle primary phase III carries a current corresponding to that carried by anode 1, as given by diagram (a), and numerically equal to that current multiplied by the ratio E_1/E'. As in this case the direction of current flow in the outer stretch of the secondary corresponding to anode 1 is opposed to the positive direction of flow in the primary winding, the instantaneous current carried by primary phase III is negative, and its actual value is thus $-0{\cdot}298 I_d \, . \, E/E'$. At the same instant primary phase I carries a current corresponding to that flowing in secondary phase 12–1, as given by diagram (*b*), and numerically equal to that current multiplied by the ratio E_2/E'. In this case the direction of

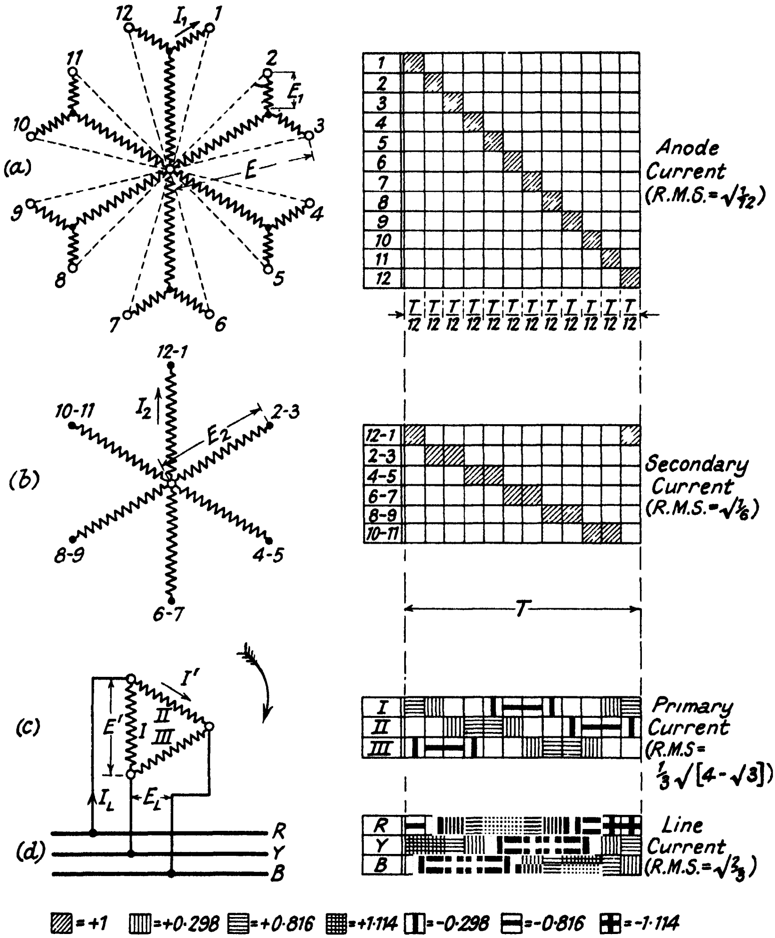
(a)
12
I_1
1
2
E_1
3
4
5
6
7
8
9
10
11
E
(b)
12-1
I_2
E_2
2-3
4-5
6-7
8-9
10-11
(c)
I'
E'
I
II
III
I_L
E_L
(d)
R
Y
B
Anode Current (R.M.S. = $\sqrt{1/12}$)
$\frac{T}{12}$
Secondary Current (R.M.S. = $\sqrt{1/6}$)
T
Primary Current (R.M.S. = $\frac{1}{3}\sqrt{[4-\sqrt{3}]}$)
Line Current (R.M.S. = $\sqrt{2/3}$)
= +1
= +0·298
= +0·816
= +1·114
= −0·298
= −0·816
= −1·114

FIG. 24. TWELVE-PHASE RECTIFICATION (FORK CONNECTION)

current flow in the inner stretch of the secondary relating to anode 1 is in the positive direction of flow in the primary winding; so that the instantaneous current carried by primary phase I is therefore positive, and hence its actual value is

$0{\cdot}816 I_d \,.\, E/E'$. By continuing this summation throughout the remainder of the voltage cycle it is found that the r.m.s. primary current, as given by Fig. 24 (*c*), is

$$I' = \sqrt{\left\{\frac{1}{12}[(0{\cdot}816)^2 + (0{\cdot}298)^2 + (-\,0{\cdot}298)^2 + (-\,0{\cdot}816)^2 \right.}$$
$$\left. .\ + (-\,0{\cdot}816)^2 + (-\,0{\cdot}298)^2 + (0{\cdot}298)^2 + (0{\cdot}816)^2]\right\}} I_d \,.\, \frac{E}{E'}$$
$$= \tfrac{1}{3}\sqrt{(4 - \sqrt{3})} \,.\, I_d \,.\, E/E' = 0{\cdot}502 I_d \,.\, E/E' \quad . \quad (20f)$$

The distribution of the line currents, given in Fig. 24(*d*), is obtained in the usual way by summation of the primary phase currents, due regard again being paid to algebraic signs as determined by the phase sequence and the direction of current flow. Taking the line currents in rotation, we may write them: $R = \mathrm{II} - \mathrm{I}$; $Y = \mathrm{I} - \mathrm{III}$; $B = \mathrm{III} - \mathrm{II}$. Their r.m.s. value is consequently

$$I_L = \sqrt{\left\{\frac{1}{12}[(-\,0{\cdot}816)^2 + (-\,0{\cdot}298)^2 + (0{\cdot}298)^2 + (0{\cdot}816)^2 \right.}$$
$$+ (1{\cdot}112)^2 + (1{\cdot}112)^2 + (0{\cdot}816)^2 + (0{\cdot}298)^2 + (-\,0{\cdot}298)^2$$
$$\left. + (-\,0{\cdot}816)^2 + (-\,1{\cdot}112)^2 + (-\,1{\cdot}112)^2]\right\}} I_d \,.\, \frac{E}{E_L}$$
$$= (\sqrt{\tfrac{2}{3}}) I_d \,.\, E/E_L = 0{\cdot}816 I_d \,.\, E/E_L . \quad . \quad . \quad . \quad . \quad (20g)$$

Secondary Copper Loading. The kVA rating of the secondary winding is given by

$$W_2 = 12E_1I_1 + 6E_2I_2 = 6I_d \times 0{\cdot}715 V_{d_0}[(2 \times 0{\cdot}298 \times 0{\cdot}289) + (0{\cdot}816 \times 0{\cdot}408)]$$
$$= 2{\cdot}17 W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20h)$$

Primary Copper Loading. Similarly, the kVA rating of the primary winding is found to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}502 I_d \,.\, E/E'$$
$$= 1{\cdot}08 W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (20i)$$

A.C. Supply Loading. The line input kVA is, similarly, given by

$$W_L = \sqrt{3} E_L I_L = (\sqrt{3}) E_L \times 0{\cdot}816 I_d \,.\, E/E_L$$
$$= 1{\cdot}01 W_d \,. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20j)$$

The mean kVA rating of the rectifier transformer is as high as $1{\cdot}625 W_d$ with this particular twelve-phase connection. At the same time it is interesting to note that the utility factor of the secondary winding is 0·46, as compared with 0·40 for a star-connected twelve-phase rectifier system. The gain due to phase-combination is in this case as much as 15 per cent.*

Referring to Fig. 24 (*c*), it is seen that the algebraic sum of the primary phase currents at every instant in the voltage cycle is not equal to zero, so that a star-connected primary winding cannot be employed. In this respect the twelve-phase fork connection differs materially from its six-phase counterpart in which symmetry of the primary currents is observed. Moreover, the ratio between line and primary currents is not equal to $\sqrt{3}$—a fact in confirmation of this asymmetry.

The Quadruple Three-phase Circuit. The disadvantage of poor utility factor associated with a simple twelve-phase circuit such as that just discussed has led to the development of composite circuits making use of phase equalizing between groups of three-phase, four-phase or six-phase systems. Of these, the quadruple three-phase circuit illustrated in Fig. 25 is probably the best known, and the most frequently used in practice, in spite of its requiring no less than three separate phase equalizers. It consists of four distinct and inter-star-connected three-phase systems relatively displaced in phase by 90 electrical degrees. The neutral points of two of these systems are connected together through one phase equalizer (*A*), and those of the remaining two systems are similarly joined through another phase equalizer (*B*). Each pair of three-phase systems thus formed operates as a six-phase system, but on the double three-phase principle discussed in the preceding chapter. The two six-phase systems so formed are in turn displaced in phase by 90 electrical degrees through the medium of the third-phase equalizer (*C*), connected between their neutral points. The first two-phase equalizers operate at triple frequency; whilst the third one makes use of harmonics of sextuple frequency to compensate the voltage difference between the two six-phase systems, and thus to give twelve-phase character to the circuit as a whole.

Referring to Fig. 25 (*a*), it is seen that the three-phase systems comprising anode groups 1–5–9 and 3–7–11 are in antiphase, and consequently together operate as a six-phase system. The same applies to the three-phase systems comprising anode groups 2–6–10 and 4–8–12. The two six-phase systems formed in this manner, and comprising anode groups 1–3–5–7–9–11 and 2–4–6–8–10–12, are in quadrature and thus in turn combine to form a composite system, possessing a twelve-phase character. With this quadruple three-phase arrangement of anode groups, there are always four anodes, one in each group, carrying current at any instant, so that each anode carries one-quarter of the full direct current I_d during one-third of the voltage cycle, i.e. over 120 electrical degrees. The r.m.s. anode loading is therefore only $\frac{1}{4}\sqrt{\frac{1}{3}}$ times the direct current delivered by the rectifier, as compared with $\sqrt{\frac{1}{12}} = \frac{1}{2}\sqrt{\frac{1}{3}}$ times the direct current in the case of simple twelve-phase rectification. This feature constitutes a still further advantage in favour of composite rectifier systems of this type.

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* In the case of the six-phase fork circuit the corresponding gain is only 1½ per cent.

As in the case of the twelve-phase fork circuit, the individual phase voltages E are obtained by phase combination of the voltages E_1 and E_2 across the outer and inner stretches of the secondary windings; and, as before, we have $E_1 = 0{\cdot}298E$ and $E_2 = 0{\cdot}816E$. But in this case the secondary phase voltage is that corresponding to three-phase operation, with $p = 3$, and its r.m.s. value is consequently

$$E = \frac{\pi}{3\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/3)} = 0{\cdot}855 V_{d_0} \quad . \quad . \quad . \quad . \quad (21a)$$

From the distribution of the anode (and secondary) currents given in Fig. 25 (a), it is seen that their r.m.s. value is

$$I = \sqrt{\left\{\frac{1}{12}[(1)^2 + (1)^2 + (1)^2 + (1)^2]\right\}}\frac{1}{4}I_d = 0{\cdot}145 I_d \quad (21b)$$

The distribution of the corresponding primary currents, shown in Fig. 25 (b), is obtained from diagram (a) as follows: Let us consider, for example, that part of the voltage cycle in which anodes 1, 2, 3 and 4 are simultaneously carrying current. Taking anode 1 first of all and remembering that, as before, the primary-to-secondary current ratio is $0{\cdot}298E/E'$ for the outer stretches, and $0{\cdot}816E/E'$ for the inner stretches of the secondary winding, then the primary currents flowing due to the currents in the inner and outer stretches of the secondary are respectively $\frac{1}{4}I_d \times 0{\cdot}816E/E'$ in phase I and $-\frac{1}{4}I_d \times 0{\cdot}298E/E'$ in phase III. Similarly, the primary currents due to the current carried by anode 2 are $\frac{1}{4}I_d \times 0{\cdot}298E/E'$ in phase I and $-\frac{1}{4}I_d \times 0{\cdot}816E/E'$ in phase III. Again, considering anode 3, the primary currents corresponding to the

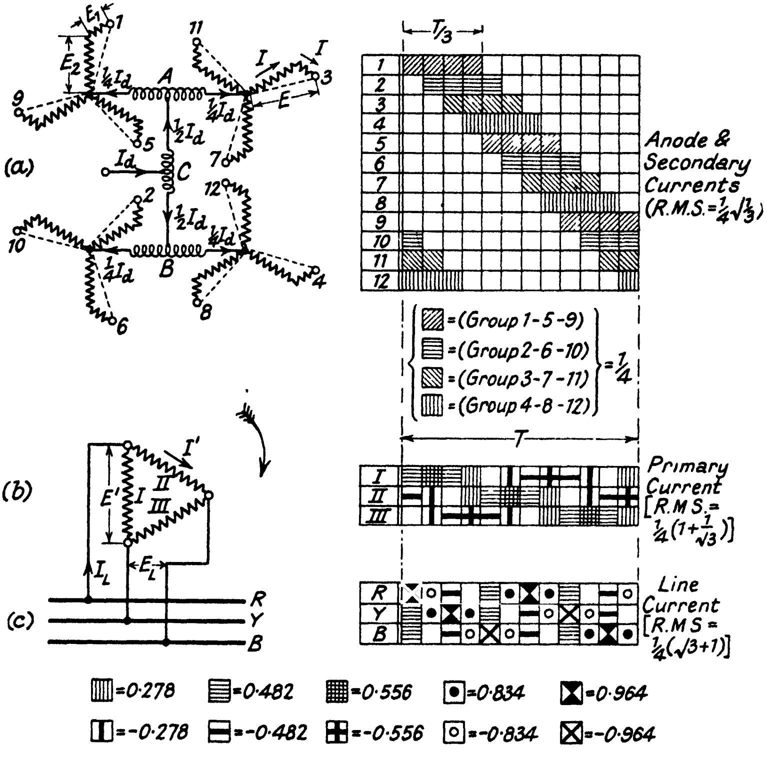

FIG. 25. QUADRUPLE THREE-PHASE RECTIFICATION

current flowing in the inner and outer stretches of the secondary windings in the anode circuit are respectively $-\frac{1}{4}I_d \times 0{\cdot}816E/E'$ in phase III and $\frac{1}{4}Id \times 0{\cdot}298E/E'$ in phase II. Finally, taking anode 4, the appropriate primary currents are $\frac{1}{4}I_d \times 0{\cdot}816E/E'$ in phase II and $-\frac{1}{4}I_d \times 0{\cdot}298E/E'$ in phase III. By addition of corresponding phase currents, we find that at this instant, when anodes 1, 2, 3 and 4 together carry the full direct current I_d, the instantaneous primary currents are

$$(1)\ \left(\frac{\sqrt{3}+1}{4\sqrt{6}}\right)I_d\,.\,\frac{E}{E'} = 0{\cdot}278I_d\,.\,\frac{E}{E'}\ \text{in phase I;}$$

$$(2)\ \left(\frac{\sqrt{3}+1}{4\sqrt{6}}\right)I_d\,.\,\frac{E}{E'} = 0{\cdot}278I_d\,.\,\frac{E}{E'}\ \text{in phase II;}$$

$$(3)\ -\left(\frac{\sqrt{3}+1}{2\sqrt{6}}\right)I_d\,.\,\frac{E}{E'} = -\,0{\cdot}556I_d\,.\,\frac{E}{E'}\ \text{in phase III.}$$

From Fig. 25 (*b*) it is seen that the r.m.s. value of the primary currents is

$$\begin{aligned} I' = \sqrt{\Big\{\tfrac{1}{12}} & [(0{\cdot}482)^2 + (0{\cdot}556)^2 + (0{\cdot}482)^2 + (0{\cdot}278)^2 \\ & + (-0{\cdot}278)^2 + (-0{\cdot}482)^2 + (-0{\cdot}556)^2 \\ & + (-0{\cdot}482)^2 + (-0{\cdot}278)^2 + (0{\cdot}278)^2]\Big\}I_d\,.\,\frac{E}{E'} \\ = \frac{\sqrt{3}+1}{4\sqrt{3}}I_d\,.\,\frac{E}{E'} &= 0{\cdot}395I_d\,.\,\frac{E}{E'} \quad . \quad . \quad . \quad (21c) \end{aligned}$$

The distribution of the line currents, shown in Fig. 25 (*c*), is obtained in the usual manner from the relation:

$$R = \text{II} - \text{I};\ Y = \text{I} - \text{III};\ B = \text{III} - \text{II}.$$

Their r.m.s. value is, in consequence, given by

$$\begin{aligned} I_L = \sqrt{\Big\{\tfrac{1}{12}} & [(-0{\cdot}964)^2 + (-0{\cdot}834)^2 + (-0{\cdot}482)^2 \\ & + (0{\cdot}482)^2 + (0{\cdot}834)^2 + (0{\cdot}964)^2 + (0{\cdot}834)^2 \\ & + (0{\cdot}482)^2 + (-0{\cdot}842) + (-0{\cdot}834)^2]\Big\}I_d\,.\,\frac{E}{E_L} \\ = \frac{\sqrt{3}+1}{4}I_d\,.\,\frac{E}{E_L} &= 0{\cdot}682I_d\,.\,\frac{E}{E_L} \quad . \quad . \quad . \quad (21d) \end{aligned}$$

Secondary Copper Loading. From Fig. 25 (*a*) it is seen that the kVA rating of the secondary winding is

$$\begin{aligned} W_2 &= 12E_1I + 12E_2I = 12 \times 0{\cdot}145I_d \times 0{\cdot}855V_{d_0}(0{\cdot}298 + 0{\cdot}816) \\ &= 1{\cdot}65W_d. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21e) \end{aligned}$$

Primary Copper Loading. Similarly, from Fig. 25 (*b*), the kVA rating of the primary winding is seen to be

$$W_1 = 3E'I' = 3E' \times 0{\cdot}395 I_d \,.\, E/E'$$
$$= 1{\cdot}01 W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21f)$$

A.C. Supply Loading. Again, from Fig. 25 (*c*), the line input kVA is given by

$$W_L = (\sqrt{3})E_L I_L = (\sqrt{3})E_L \times 0{\cdot}682 I_d \,.\, E/E_L$$
$$= 1{\cdot}01 W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21g)$$

The two phase equalizers *A* and *B* operate in exactly the same way as the phase equalizer associated with the double three-phase circuit discussed in the previous chapter. But their kVA rating is only one-half the rating of the phase equalizer for the six-phase connection, as each carries a current equal to only $\frac{1}{4}I_d$ in place of $\frac{1}{2}I_d$. The equivalent kVA rating of each of these two third-harmonic phase equalizers is thus

$$2 \times \frac{1}{3} \,.\, \frac{V_{d_0}}{4} \times \frac{I_d}{4} = \frac{1}{24} W_d \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21h)$$

The function of the third phase equalizer *C* is to equalize the instantaneous potential difference between the six-phase systems constituted by the two phase-groups 1–3–5–7–9–11 and 2–4–6–8–10–12. The voltage across each of its two windings, being the difference between the mean potentials of these two phase-groups and the phase voltage of one six-phase system, has therefore a triangular wave-form also, and in this case its amplitude is approximately $\frac{1}{16} \,.\, (\sqrt{2})E$, and its r.m.s. value may therefore be taken as being equal to $\frac{1}{16} \,.\, V_{d_0}$. This voltage is produced by a sixth-harmonic magnetizing current, superimposed on the direct current flowing in the windings of the phase equalizer, so that looking upon the latter as a normal two-winding transformer operating at the frequency of the alternating-current supply, its equivalent kVA rating is seen to be

$$2 \times \frac{1}{6} \,.\, \frac{V_{d_0}}{16} \times \frac{I_d}{2} = \frac{1}{96} W_d \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21i)$$

The total equivalent kVA rating of all three-phase equalizers is therefore $0{\cdot}09 W_d$; so that the mean kVA rating of the transformer unit as a whole is $1{\cdot}42 W_d$, which compares favourably with the corresponding figure of $1{\cdot}35 W_d$ obtained for the double three-phase circuit. In any case, it represents a reduction of no less than 13 per cent as compared with the twelve-phase fork circuit.

It is interesting to note that the quadruple three-phase circuit also permits of a star-connected transformer primary, as may be seen from Fig. 25 (*b*); and here again it will be found that its kVA rating is the same as that of the delta-connected winding considered above. That the algebraic sum of the individual phase currents in the primary winding is zero at every instant is also evidenced by the fact that the r.m.s. value of the line current is equal to $\sqrt{3}$ times that of the primary current.

The Triple Four-phase Circuit. In the same way that the preceding circuit may be looked upon as an outcome of the well-known and widely-used double three-phase arrangement of a six-phase rectifier system, so the triple four-phase circuit (Fig. 26) may be regarded as a logical development from the triple single-phase circuit discussed at the end of the previous chapter. It consists of three distinct and fork-connected four-phase systems relatively displaced in phase by 120 electrical degrees, and having their neutral points joined through a three-core phase equalizer. With this arrangement of anode groups there are always three anodes, one in each group, carrying current at any instant; thus each anode carries one-third of the full direct current I_d during one-quarter of the voltage cycle, i.e. over 90 electrical degrees. The r.m.s. anode loading is therefore $\frac{1}{3}\sqrt{\frac{1}{4}}$ times the direct current delivered by the rectifier, as compared with $\frac{1}{4}\sqrt{\frac{1}{3}}$ times the direct current in the case of quadruple three-phase rectification—an increase of 15 per cent.

As in the case of the two previous circuits, the individual phase voltages E are obtained by phase-combination of the voltages E_1 and E_2 across the outer and inner stretches of the secondary windings. But here, as may be seen from Fig. 26 (*a*), the relations are: $E_1 = 0{\cdot}816E$ and $E_2 = 0{\cdot}298E$. The secondary phase voltage is that corresponding to four-phase operation, with $p = 4$, so that its r.m.s. value is

$$E = \frac{\pi}{4\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/4)} = 0{\cdot}785 V_{d_0} \quad . \quad . \quad . \quad (22a)$$

From the anode-current distribution given in Fig. 26 (*a*), we have for the r.m.s. value of the anode currents

$$I_1 = \sqrt{\left\{\frac{1}{12}[(1)^2 + (1)^2 + (1)^2]\right\}} \cdot \frac{1}{3}I_d = 0{\cdot}167I_d \qquad (22b)$$

By reason of the fork connection of each of the three four-phase systems, the inner stretches of the secondary windings are utilized twice as often as the outer stretches which carry the anode currents. This is shown by the secondary-current distribution given in Fig. 26 (*b*), from which

$$I_2 = \sqrt{\left\{\frac{1}{12}[(1)^2 + (1)^2 + (1)^2 + (1)^2 + (1)^2 + (1)^2]\right\}} \cdot \frac{1}{3}I_d$$
$$= 0{\cdot}236I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (22c)$$

The corresponding distribution of the primary currents is shown in Fig. 26 (*c*), and is derived as follows: Consider, for instance, that part of the voltage cycle during which anodes 1, 2, and 3 are simultaneously carrying current. Referring to diagram (*a*), the phase current ratio, primary to secondary, is $0{\cdot}816E/E'$ for the outer stretches and $0{\cdot}298E/E'$ for the inner stretches, so that taking anode 1, in the first place, then the primary currents flowing due to current in the inner and outer stretches of the secondary winding are respectively $-\frac{1}{3}I_d \times 0{\cdot}298E/E'$ in phase II and $\frac{1}{3}I_d \times 0{\cdot}816E/E'$ in phase I. Similarly, the primary currents flowing due to the current in the windings connected to anode 2 are $-\frac{1}{3}I_d \times 0{\cdot}298E/E'$ in phase III and $\frac{1}{3}I_d \times 0{\cdot}816E/E'$ in phase II. Again, considering anode 3, the primary currents corresponding to the current flowing in the inner and outer stretches of the secondary windings in the anode circuit are $\frac{1}{3}I_d \times 0{\cdot}298E/E'$ in phase I and $-\frac{1}{3}I_d \times 0{\cdot}816E/E'$ in phase III. By addition of corresponding phase currents, we thus find that at this instant, when anodes 1, 2, and 3 together carry the full direct current I_d, the instantaneous primary currents are

$$(1)\ \left(\frac{\sqrt{3}+1}{3\sqrt{2}}\right)I_d \cdot \frac{E}{E'} = 0{\cdot}643I_d \cdot \frac{E}{E'} \text{ in phase I;}$$

$$(2)\ -\left(\frac{\sqrt{3}-1}{3\sqrt{6}}\right)I_d \cdot \frac{E}{E'} = -\,0{\cdot}099I_d \cdot \frac{E}{E'} \text{ in phase II;}$$

$$(3)\ -\left(\frac{\sqrt{3}+1}{3\sqrt{6}}\right)I_d \cdot \frac{E}{E'} = -\,0{\cdot}371I_d \cdot \frac{E}{E'} \text{ in phase III.}$$

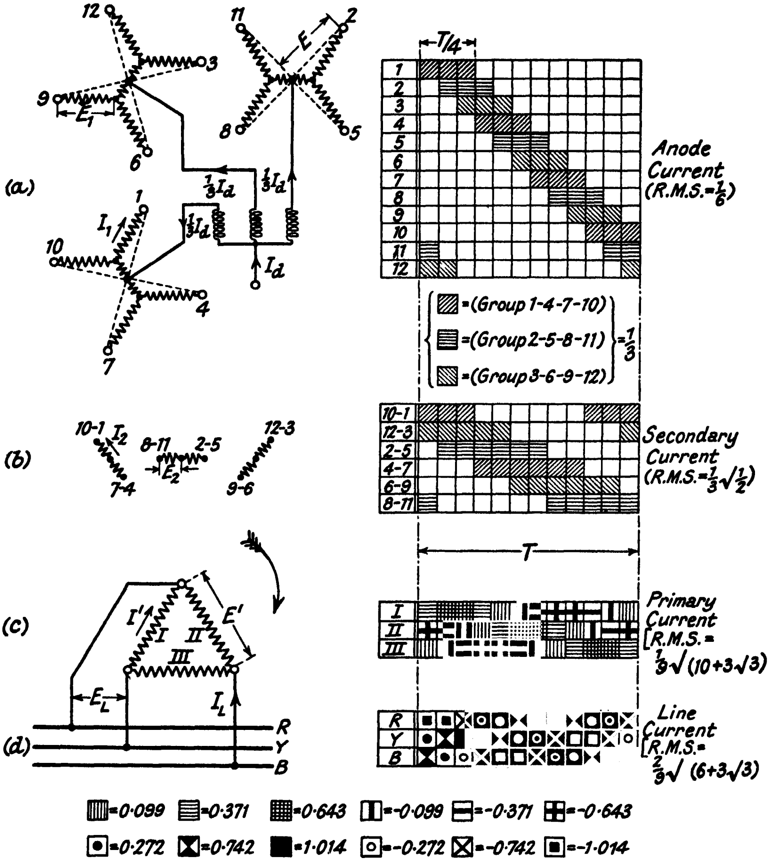

Fig. 26. Triple Four-phase Rectification

From Fig. 26 (*c*) it is seen that the r.m.s. value of the primary currents is therefore

$$I' = \sqrt{\Big\{\frac{1}{12}[(0\cdot371)^2 + (0\cdot643)^2 + (0\cdot643)^2 + (0\cdot371)^2 + (0\cdot099)^2 + (-0\cdot099)^2 + (-0\cdot371)^2 + (-0\cdot643)^2 + (-0\cdot643)^2 + (-0\cdot371)^2 + (-0\cdot643)^2 + (-0\cdot371)^2 + (-0\cdot099)^2 + (0\cdot099)^2]\Big\}}\, I_d \cdot \frac{E}{E'}$$

$$= \tfrac{1}{9}\sqrt{[10 + 3\sqrt{3}]}\, I_d \,.\, E/E' = 0\cdot433 I_d \,.\, E/E' \quad . \quad (22d)$$

The distribution of the line currents, given in Fig. 26 (*d*), is obtained in the usual way from the relation:

$$R = \text{II} - \text{I}; \quad Y = \text{I} - \text{II}; \quad B = \text{III} - \text{II}.$$

Their r.m.s. value is consequently given by

$$\begin{aligned} I_L = \sqrt{\Big\{}\tfrac{1}{12}[(-1{\cdot}014)^2 + (-1{\cdot}014)^2 + (-0{\cdot}742)^2 \\ + (-0{\cdot}272)^2 + (0{\cdot}272)^2 + (0{\cdot}742)^2 + (1{\cdot}014)^2 \\ + (1{\cdot}014)^2 + (0{\cdot}742)^2 + (0{\cdot}272)^2 + (-0{\cdot}272)^2 \\ + (-0{\cdot}742)^2]\Big\}I_d \,.\, \frac{E}{E'} \\ = \frac{2\sqrt{3}}{9}\sqrt{[2 + \sqrt{3}]}I_d \,.\, \frac{E}{E_L} = 0{\cdot}743 I_d \,.\, \frac{E}{E_L} \quad . \quad . \quad (22e) \end{aligned}$$

Secondary Copper Loading. From Fig. 26 (*a*), the kVA rating of the secondary winding is

$$\begin{aligned} W_2 &= 12E_1I_1 + 6E_2I_2 = (12 \times 0{\cdot}816E \times 0{\cdot}167I_d) \\ &\qquad + (6 \times 0{\cdot}298E \times 0{\cdot}236I_d) \\ &= (1{\cdot}632 + 0{\cdot}419)EI_d = 2{\cdot}051 \times 0{\cdot}785V_{d_0}I_d \\ &= 1{\cdot}61W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22f) \end{aligned}$$

Primary Copper Loading. Similarly, from Fig. 26 (*c*), the kVA rating of the primary winding is

$$\begin{aligned} W_1 &= 3E'I' = 3E' \times 0{\cdot}433I_d \,.\, E/E' \\ &= 1{\cdot}02W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22g) \end{aligned}$$

A.C. Supply Loading. Again, from Fig. 26 (*d*), the line input kVA is

$$\begin{aligned} W_L &= (\sqrt{3})E_LI_L = (\sqrt{3})E_L \times 0{\cdot}743I_d \,.\, E/E_L \\ &= 1{\cdot}01W_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22h) \end{aligned}$$

The phase equalizer functions in precisely the same manner as the three-core phase equalizer associated with the triple single-phase circuit discussed at the end of the previous chapter; but in the present case the voltage across each of its three windings, being the difference between the mean potentials of all three phase-groups (1–4–7–10, 2–5–8–11, and 3–6–9–12) and the phase voltage of one four-phase system, is of quadruple frequency; and its r.m.s. value is approximately equal to $\frac{1}{8}V_{d_0}$.

Hence, looking upon the phase equalizer as a normal three-winding auto-transformer operating at the frequency of the alternating supply, its equivalent kVA rating is

$$3 \times \frac{1}{4} \cdot \frac{V_{d_0}}{8} \times \frac{I_d}{3} = \frac{1}{32} W_d \quad . \quad . \quad . \quad . \quad . \qquad (22i)$$

The mean kVA rating of the transformer unit as a whole is therefore $1{\cdot}35 W_d$ for the triple four-phase circuit, as compared with $1{\cdot}42 W_d$ for the quadruple three-phase circuit. The utilization of the former circuit is thus better by 5 per cent, whilst the reduction in mean rating as compared with the twelve-phase fork circuit is as much as 17 per cent.

Referring to Fig. 26 (*c*), it is seen that the algebraic sum of the primary phase currents at every instant in the voltage cycle is not equal to zero, so that a star-connected primary winding cannot be employed. This is confirmed by the fact that the ratio between the line and primary currents is not $\sqrt{3} : 1$.

The Double Six-phase Circuit. The double six-phase circuit, which has been developed by the author, is essentially a compromise in that it furnishes an arrangement of transformer connection that is neither unduly complicated as regards phase-combination, nor too wasteful as far as the expenditure of valuable kVA on phase equalizers is concerned, and is at the same time one which gives a twelve-phase character to the rectifier system as a whole.

In a sense, it is a logical development from the six-phase fork circuit discussed in the preceding chapter, but the method of phase-combination employed to obtain two six-phase systems displaced in phase by a right angle does not permit of the same degree of symmetry in the secondary phases. For this reason the secondary kVA rating is some 4 per cent greater than in the case of the six-phase fork connection.

The double six-phase circuit (Fig. 27), then, consists of two distinct and fork-connected six-phase systems relatively displaced in phase by 90 electrical degrees, and having their neutral points joined through a two-core phase equalizer; so that two anodes, one from each six-phase group, together always carry the total current delivered by the rectifier system. Each anode, therefore, carries one-half of the full direct current during one-sixth of the voltage cycle, i.e. over 60 electrical degrees. The r.m.s. anode loading is consequently $\frac{1}{2}\sqrt{\frac{1}{6}}$

times the direct current, as compared with $\sqrt{\frac{1}{12}}$ times the direct current in the case of the twelve-phase fork circuit—a reduction of 30 per cent. With this circuit also, the individual phase voltages E are obtained by phase-combination of voltages having values of $0{\cdot}298E$ and $0{\cdot}816E$. The secondary phase voltage is that corresponding to six-phase operation, with $p = 6$, so that its r.m.s. value is

$$E = \frac{\pi}{6\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/6)} = 0{\cdot}74 V_{d_0} \quad . \quad . \quad . \quad . \quad (23a)$$

The anode-current distribution is given in Fig. 27 (a), from which

$$I_1 = \sqrt{\left\{\frac{1}{12}[(1)^2 + (1)^2]\right\}} \cdot \tfrac{1}{2} I_d = 0{\cdot}204 I_d \quad . \quad . \quad (23b)$$

Moreover, by reason of the fork connection of each six-phase anode-group, the inner stretches of the secondary winding are utilized twice as frequently as the outer stretches carrying the anode currents. This is illustrated by the secondary-current distribution diagram given in Fig. 27 (b), from which

$$I_2 = \sqrt{\left\{\frac{1}{12}[(1)^2 + (1)^2 + (1)^2 + (1)^2]\right\}} \cdot \tfrac{1}{2} I_d = 0{\cdot}289 I_d \quad (23c)$$

The corresponding distribution of the primary currents is shown in Fig. 27 (c), and is derived in the usual way from a consideration of the current-flow in the various primary phases produced by the anode and secondary currents, due regard being paid not only to algebraic sign, but to the current ratios for the different parts of the secondary winding as well. For example, during that part of the voltage cycle in which anodes 6 and 7 are simultaneously carrying the full direct current I_d, the instantaneous primary currents are

$$(1) \; -\left(\sqrt{\frac{2}{3}}\right) I_d \cdot \frac{E}{E'} = -\,0{\cdot}816 I_d \cdot \frac{E}{E'} \text{ in phase I;}$$

$$(2) \; \left(\frac{\sqrt{3}-1}{2\sqrt{6}}\right) I_d \cdot \frac{E}{E'} = 0{\cdot}149 I_d \cdot \frac{E}{E'} \text{ in phase II;}$$

$$(3) \; \left(\frac{\sqrt{3}-1}{2\sqrt{6}}\right) I_d \cdot \frac{E}{E'} = 0{\cdot}149 I_d \cdot \frac{E}{E'} \text{ in phase III.}$$

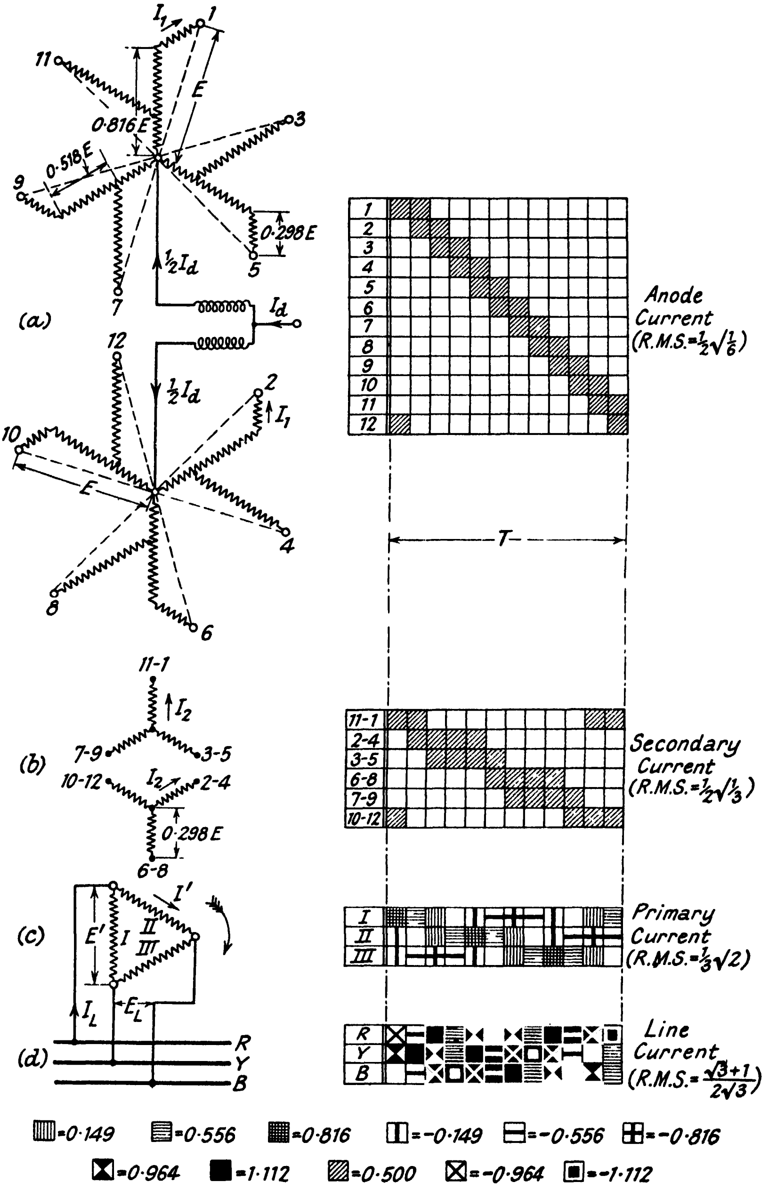

FIG. 27. DOUBLE SIX-PHASE RECTIFICATION

From Fig. 27 (*c*) it is seen that the r.m.s. value of the primary currents is, therefore,

$$I' = \sqrt{\left\{\frac{1}{12}[(0{\cdot}816)^2 + (0{\cdot}556)^2 + (0{\cdot}149)^2 + (-0{\cdot}149)^2 + (-0{\cdot}556)^2 + (-0{\cdot}816)^2 + (-0{\cdot}556)^2 + (-0{\cdot}144)^2 + (0{\cdot}149)^2 + (0{\cdot}556)^2]\right\}} I_d \,.\, \frac{E}{E'}$$

$$= (\tfrac{1}{3}\sqrt{2})I_d \,.\, E/E' = 0{\cdot}471 I_d \,.\, E/E' \qquad (23d)$$

From the line-current distribution given in Fig. 27 (*d*) and obtained, in the usual way, from the relation:

$$R = \mathrm{II} - \mathrm{I};\ Y = \mathrm{I} - \mathrm{III};\ B = \mathrm{III} - \mathrm{II};$$

we have, for the r.m.s. value of the line currents,

$$I_L = \sqrt{\left\{\frac{1}{12}[(0{\cdot}964)^2 + (0{\cdot}556)^2 + (-0{\cdot}556)^2 + (-0{\cdot}964)^2 + (-1{\cdot}112)^2 + (-0{\cdot}964)^2 + (-0{\cdot}556)^2 + (0{\cdot}556)^2 + (0{\cdot}964)^2 + (1{\cdot}112)^2]\right\}} I_d \,.\, \frac{E}{E_L}$$

$$= \frac{\sqrt{3}+1}{2\sqrt{3}} I_d \,.\, \frac{E}{E_L} = 0{\cdot}787 I_d \,.\, \frac{E}{E_L} \qquad (23e)$$

Secondary Copper Loading. From Fig. 27 (*a*), the kVA rating of the secondary winding is

$$\begin{aligned} W_2 &= (12 \times 0{\cdot}816E \times 0{\cdot}204I_d) + (6 \times 0{\cdot}298E \times 0{\cdot}289I_d) \\ &= (2{\cdot}000 + 0{\cdot}518)EI_d \\ &= 1{\cdot}86W_d \qquad (23f) \end{aligned}$$

Primary Copper Loading. Similarly, from Fig. 27 (*c*), the kVA rating of the primary winding is

$$\begin{aligned} W_1 &= 3E'I' = 3E' \times 0{\cdot}471I_d \,.\, E/E' \\ &= 1{\cdot}05W_d \qquad (23g) \end{aligned}$$

A.C. Supply Loading. Again, from Fig. 27 (*d*), the line input kVA is

$$\begin{aligned} W_L &= (\sqrt{3})E_L I_L = (\sqrt{3})E_L \times 0{\cdot}787I_d \,.\, E/E_L \\ &= 1{\cdot}01W_d \qquad (23h) \end{aligned}$$

The phase equalizer is identical with the third-phase equalizer —*C* in Fig. 25 (*a*)—employed in the quadruple three-phase circuit, and its equivalent kVA rating is therefore

$$2 \times \frac{1}{6} \cdot \frac{V_{d_0}}{16} \times \frac{I_d}{2} = \frac{1}{96} W_d \quad . \quad . \quad . \quad . \quad . \qquad (23i)$$

The mean kVA rating of the rectifier transformer unit as a whole is therefore $1{\cdot}455 W_d$ for the double six-phase circuit, as compared with $1{\cdot}625 W_d$ and $1{\cdot}42 W_d$ for the twelve-phase and six-phase fork circuits respectively. With double six-phase operation, therefore, the utilization of the transformer is intermediate between that occurring under conditions of simple six-phase and twelve-phase working. Compared with either of the two previous phase-equalizing circuits having twelve-phase character, the utility factor is, however, not quite so good. In point of fact, the double six-phase circuit shows a 2½ per cent poorer utilization than the quadruple three-phase circuit; whilst the reduction in utilization is about 7½ per cent as compared with the triple four-phase circuit. On the other hand, it is to be remembered that only a single and two-core phase equalizer is required, and as this operates by virtue of harmonics of sextuple frequency, the sudden rise in voltage occurring at no-load of the rectifier system is only 3½ per cent, which is not likely to be objectionable in practice. In the case of the other two phase-equalizing circuits, the voltage rise is either 20 per cent or 10 per cent, so that special means for providing harmonic excitation of the phase equalizers are likely to be a practical necessity.

Here again the algebraic sum of the primary phase currents at every instant in the voltage cycle is not equal to zero, as may be seen from Fig. 27 (*c*). Thus a star-connected primary winding cannot be used with this particular arrangement of rectifier transformer. Hence also the fact that the r.m.s. value of the line current is not equal to $\sqrt{3}$ times that of the primary current.

The Twelve-phase Series Circuit. Another arrangement which, like the foregoing, employs fork connection of the transformer and operates on the principle of phase equalizing—but without the actual inclusion of any phase-equalizing device in the circuit—is the twelve-phase circuit due to Krämer* and generally known as the *series* connection.

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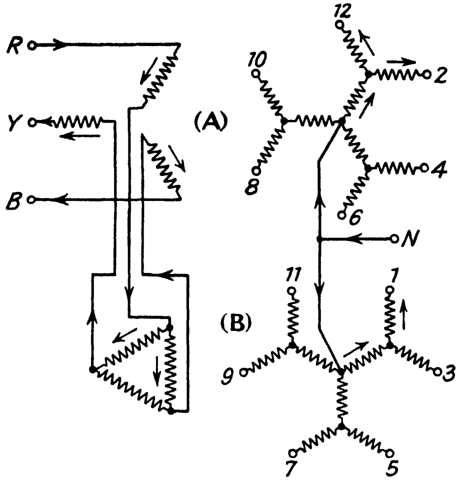
* C. Krämer: "A New Twelve-Phase Transformer Connection for Steel-tank Rectifiers," *Elektrotechnisches Zeitschrift*, 1929, Vol. 50. p. 303.

In the opinion of the author it would appear to be the rectifier circuit *par excellence*, in which the claims made for twelve-phase working—and on theoretical grounds these cannot be disputed—viz. better inherent voltage regulation, practically non-fluctuating output voltage, good power factor, and high efficiency are all substantiated in practice; whilst its peculiar mode of operation enables it to escape not only the disadvantage of poor utilization which is characteristic of the simple types of twelve-phase circuit, but also the drawback of requiring the expenditure of valuable kVA on phase-equalizing devices.

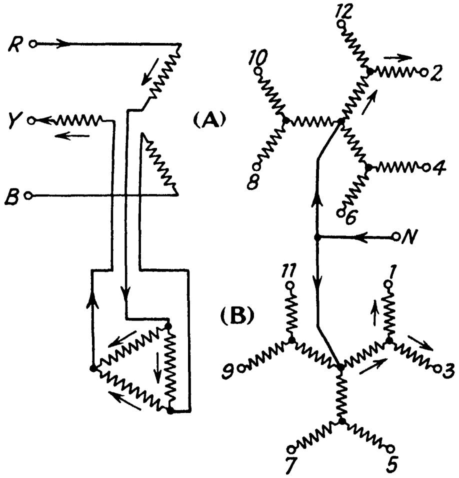
This interesting twelve-phase circuit (Fig. 28) essentially comprises two six-phase fork-connected transformers whose primary windings are connected in series in such a manner that the fluxes of the two transformers are displaced by $\pi/6$, and whose secondary windings are connected in parallel by directly joining their neutral points to the negative pole of the rectifier system. In this way the two six-phase systems combine to form a rigid twelve-phase system which is symmetrical and stable at all loads.

It is seen from Fig. 28 that the requisite phase displacement between the two six-phase systems is obtained by connecting the primary winding of transformer *A* in star (open) and that of transformer *B* in delta (closed). The two three-limbed transformer cores are generally arranged one on top of the other, or side by side in a common tank. By reason of the series connection of the primary windings, the rectifier load is divided equally between the two six-phase anode groups, and because of the fork connection of the secondary windings the load current is always distributed over three rectifier anodes at any instant. In other words, the total secondary copper loading is that corresponding to a quarter-phase connection and consequently each anode carries current for one-quarter of a cycle, that is, over 90 electrical degrees. Due to this large measure of phase equalizing, the kVA rating of the transformer unit as a whole is very much reduced as compared with the majority of twelve-phase connected transformers, and is actually 5 per cent less than that of the equivalent six-phase fork-connected transformer.

The distribution of the load current over the three simultaneously working anodes is not uniform, as the number of turns per primary phase is not the same for both transformers.



(a) Current Distribution between Anodes.



(b) Current Distribution 30° later than in (a)

FIG. 28. THE TWELVE-PHASE SERIES CIRCUIT

In fact, the numbers of turns in the primary windings of *A* (star) and *B* (delta) are in the ratio of $1 : \sqrt{3}$, so that the anode currents produced by the flow of current in the primary phases of *A* and *B* must be in the ratio of $\sqrt{3} : 1$. Hence the load current divides between the three anodes in the ratios $1/(2 + \sqrt{3})$, $(\sqrt{3})/(2 + \sqrt{3})$, and $1/(2 + \sqrt{3})$, and the individual anode currents have therefore a stepped wave-form. During the first 30 electrical degrees of its current-conducting period, each anode carries a current equal to $I_d/(2 + \sqrt{3})$. During the middle period of 30 electrical degrees the current carried has the value $(\sqrt{3})I_d/(2 + \sqrt{3})$; whilst in the final 30-degree period of current conduction the anode current reverts again to its original value of $I_d/(2 + \sqrt{3})$. The distribution of the load current for the 30-degree period in which anodes 12, 1, and 2 operate together is shown in Fig. 28 (*a*). The corresponding primary current-flow is also shown by the arrows in the diagram, and it is seen that current is drawn from line *R* and returned to lines *Y* and *B*. During the next 30-degree period, when the load current is carried simultaneously by anodes 1, 2, and 3, the conditions on the primary side alter, and current is drawn from line *R* and returned to line *Y*; whilst line *B* neither takes nor supplies current, as shown in Fig. 28 (*b*). From the diagrams it is seen, also, that alternately two and three primary phases carry current; and that when *A* has two of its primary phase-windings loaded, all three phases of *B*'s primary winding carry current, and *vice versa*. In this way, therefore, and in spite of the peculiar *modus operandi* of the transformer unit as a whole, the requisite symmetry in the two sets of primary phase currents is obtained; and a little consideration will show that, as the result of this symmetry, each transformer carries one-half of the total load on the rectifier system.

As the twelve-phase series arrangement operates in the above manner as a quarter-phase system, with $p = 4$, the secondary phase voltage has an r.m.s. value equal to

$$E = \frac{\pi}{4\sqrt{2}} \cdot \frac{V_{d_0}}{\sin(\pi/4)} = 0{\cdot}785 V_{d_0}. \qquad (24a)$$

The anode current distribution is shown diagrammatically in Fig. 29 (*a*) and is derived from the load-current distribution discussed above in connection with Fig. 28. From the diagram it is seen that the r.m.s. value of the anode current is

$$I_1 = \frac{1}{2 + \sqrt{3}} \cdot \sqrt{\left\{\frac{1}{12}[(1)^2 + (\sqrt{3})^2 + (1)^2]\right\}} I_d$$

$$= \frac{I_d}{2 + \sqrt{3}} \cdot \sqrt{\frac{5}{12}} = 0{\cdot}173 I_d \qquad (24b)$$

By reason of the fork connection of each six-phase secondary, the inner stretches of the winding are utilized twice as often as the outer stretches, which carry the anode currents. This is shown by the distribution diagram of Fig. 29 (*b*), from which the r.m.s. secondary current is seen to be

$$I_2 = \frac{1}{2+\sqrt{3}} \cdot \sqrt{\left[\frac{1}{12}\left\{(\sqrt{3})^2 + (1)^2 + (1)^2 + (\sqrt{3})^2 + (2)^2\right\}\right]} I_a$$

$$= \frac{I_d}{2+\sqrt{3}} = 0{\cdot}268 I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (24c)$$

The corresponding primary current distribution is illustrated by the diagram of Fig. 29 (*c*), and is obtained by direct summation of the anode and secondary currents given in diagrams (*a*) and (*b*), due regard being paid to algebraic sign as determined by the phase sequence and the direction of current flow in individual phases. Using the notation given in the diagrams, we may write

$$\mathrm{I} = (1) + (3) - (7\text{–}9); \ \mathrm{II} = (5) + (7) - (11\text{–}1);$$
$$\mathrm{III} = (9) + (11) - (3\text{–}5);$$

and

$$\mathrm{IV} = (8\text{–}10) - (2) - (4); \ \mathrm{V} = (12\text{–}2) - (6) - (8);$$
$$\mathrm{VI} = (4\text{–}6) - (10) - (12).$$

Neglecting for the moment all consideration of the primary-to-secondary current ratios, and regarding, for example, the 30-degree period of the voltage cycle during which anodes 12, 1, and 2 together carry the load current I_d, we obtain for the instantaneous currents in the two primary windings

$$\mathrm{I} = (1) = \frac{(\sqrt{3})I_d}{2+\sqrt{3}}; \ \mathrm{II} = -(11\text{–}1) = -\frac{(\sqrt{3})I_d}{2+\sqrt{3}}; \ \mathrm{III} = 0;$$

and

$$\mathrm{IV} = -(2) = -\frac{I_d}{2+\sqrt{3}}; \ \mathrm{V} = (12\text{–}2) = \frac{2I_d}{2+\sqrt{3}};$$
$$\mathrm{VI} = -(12) = -\frac{I_d}{2+\sqrt{3}}.$$

It is these values which are actually given in the distribution diagram of Fig. 29 (*c*); but they are only equivalent values, referred to the secondary winding, and must be corrected to take into account the turns-ratios of the transformers before the r.m.s. values can be arrived at.

In the case of the Δ-primary winding, the current ratio, primary to secondary, is $E_1/E'_\Delta = E_2/E'_\Delta = E/(\sqrt{3})E'_\Delta$; whilst in the case of the Y-primary winding the corresponding ratio is $E_1/E'_Y = E_2/E'_Y = E/(\sqrt{3})E'_Y$. Furthermore, as each transformer carries half the total load on the rectifier system, the line voltage divides itself equally between the two primaries, since these are in series; so that we have $E'_Y = \frac{1}{2} . E_L/\sqrt{3}$ and $E'_\Delta = \frac{1}{2} . E_L$; or, denoting the phase voltage of the alternating-current supply system by E', we have

$$E'_Y = \frac{1}{2} . E', \text{ and } E'_\Delta = \frac{\sqrt{3}}{2} . E'^{*}$$

Consequently for phases I, II, and III the primary-to-secondary current ratio is $2E/3E'$, whilst for phases IV, V, and VI it is $2E/\sqrt{3}E'$. The Y-primary current is thus $\sqrt{3}$ times the Δ-primary current, as is to be expected in view of the inherent symmetry of the fork connection (*cf.* page 54).

From Fig. 29 (*c*) the r.m.s. value of the Δ-primary current is seen to be

$$\begin{aligned} I'_\Delta = \frac{1}{2+\sqrt{3}}\sqrt{\Big\{\frac{1}{12}[}&(\sqrt{3})^2 + (2)^2 + \sqrt{(3)^2} + (1)^2 + (-1)^2 \\ &+ (-\sqrt{3})^2 + (-2)^2 + (-\sqrt{3})^2 + (-1)^2 \\ &+ (1)^2]\Big\}I_d . \frac{2E}{3E'} \\ = \frac{2\sqrt{2}}{3(2+\sqrt{3})} I_d . \frac{E}{E'} &= 0{\cdot}253 I_d . E/E' \quad . \quad . \quad (24d) \end{aligned}$$

whilst the r.m.s. value of the Y-primary current is similarly

$$\begin{aligned} I'_Y = \frac{1}{2+\sqrt{3}}\sqrt{\Big\{\frac{1}{12}[}&(-1)^2 + (-\sqrt{3})^2 + (-2)^2 \\ &+ (-\sqrt{3})^2 + (-1)^2 + (1)^2 + (\sqrt{3})^2 + (2)^2 \\ &+ (\sqrt{3})^2 + (1)^2]\Big\}I_d . \frac{2E}{(\sqrt{3})E'} \\ = \frac{2}{2+\sqrt{3}} . \sqrt{\frac{2}{3}}I_d . \frac{E}{E'} &= 0{\cdot}438 I_d . \frac{E}{E'} \quad . \quad . \quad (24e) \end{aligned}$$

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* This relation also indicates that the number of turns per phase on the primary sides of the two transformers is in the ratio 1 : $\sqrt{3}$ (star : delta), as mentioned on p. 88.

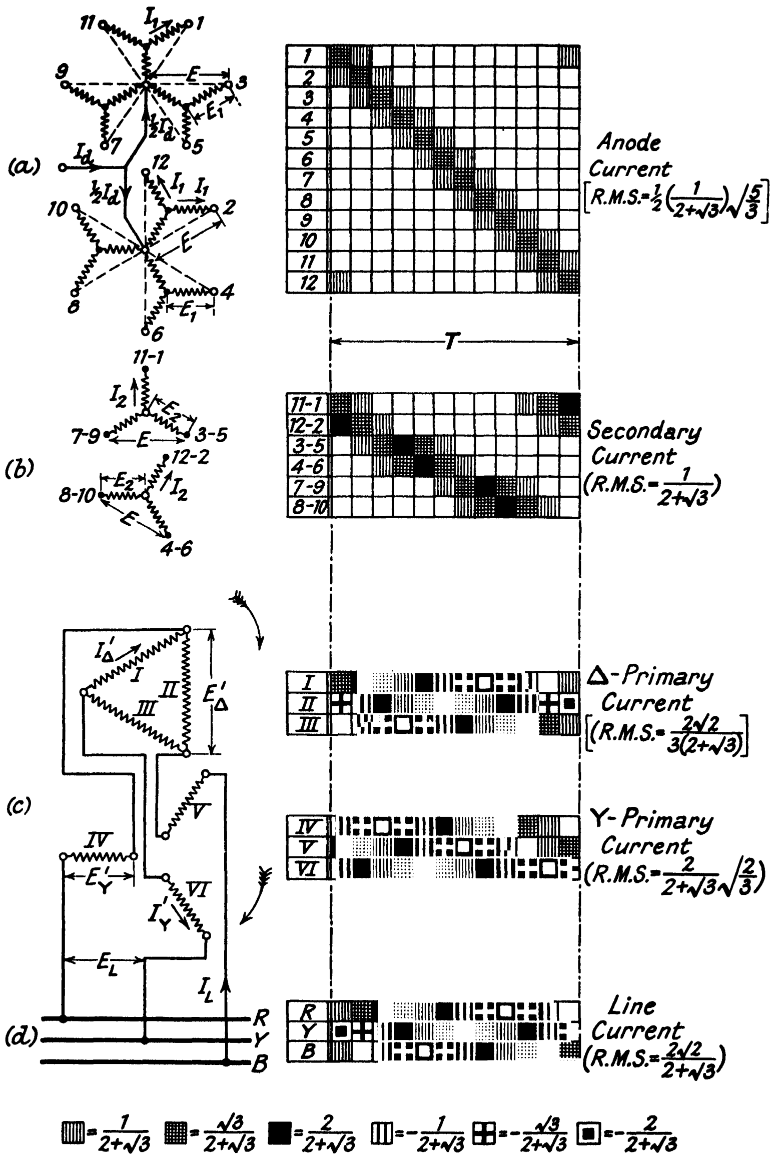

FIG. 29. TWELVE-PHASE SERIES RECTIFICATION

The line-current distribution is shown in Fig. 29 (*d*), and is obviously the same as for the Y-primary currents, so that we have for the r.m.s. value of the line current

$$I_L = 0{\cdot}438 I_d \,.\, E/E' = 0{\cdot}759 I_d \,.\, E/E_L \qquad (24f)$$

Secondary Copper Loading. From Figs. 29 (*a*) and (*b*) we obtain for the kVA rating of the combined secondary windings

$$\begin{aligned} W_2 &= 12E_1I_1 + 6E_2I_2 \\ &= \left[12 \cdot \frac{E}{\sqrt{3}} \cdot \frac{1}{2}\left(\frac{1}{2+\sqrt{3}}\right)\left(\sqrt{\frac{5}{3}}\right)I_d\right] + \left[6 \cdot \frac{E}{\sqrt{3}} \cdot \frac{I_d}{2+\sqrt{3}}\right] \\ &= \frac{2\sqrt{3}}{2+\sqrt{3}}\left(\sqrt{\frac{5}{3}} + 1\right)EI_d = \frac{\pi}{2}\left(\frac{\sqrt{5}+\sqrt{3}}{2+\sqrt{3}}\right)V_{d_0}I_d \\ &= 1{\cdot}67 W_d \qquad (24g) \end{aligned}$$

Primary Copper Loading. Similarly, from Fig. 29 (*c*), we have for the kVA rating of the combined primary windings

$$\begin{aligned} W_1 &= 3E'_\Delta I'_\Delta + 3E'_Y I'_Y \\ &= \left[3 \cdot \frac{(\sqrt{3}E')}{2} \cdot \frac{2\sqrt{2}}{3(2+\sqrt{3})}I_d \cdot \frac{E}{E'}\right] \\ &\qquad + \left[3 \cdot \frac{E'}{2} \cdot \frac{2}{2+\sqrt{3}} \cdot \left(\sqrt{\frac{2}{3}}\right)I_d \cdot \frac{E}{E'}\right] \\ &= \left(\frac{2\sqrt{6}}{2+\sqrt{3}}\right)EI_d = \frac{\pi}{2}\left(\frac{\sqrt{6}}{2+\sqrt{3}}\right)V_{d_0} I_d \\ &= 1{\cdot}03 W_d \qquad (24h) \end{aligned}$$

A.C. Supply Loading. Again, from Fig. 29 (*d*), the line input kVA is

$$\begin{aligned} W_L &= (\sqrt{3})E_L I_L = (\sqrt{3})E_L \cdot \frac{2\sqrt{2}}{2+\sqrt{3}}I_d \cdot \frac{E}{E_L} = \left(\frac{2\sqrt{6}}{2+\sqrt{3}}\right)EI_d \\ &= 1{\cdot}03 W_d \qquad (24i) \end{aligned}$$

The mean kVA rating of the transformer combination is therefore only $1{\cdot}35 W_d$, which figure represents a considerable improvement on that obtained with all other twelve-phase systems of rectification excepting the triple four-phase circuit. The twelve-phase series circuit has the advantage over the latter that no phase equalizer is required. At the same time, although the degree of phase equalizing is the same for both arrangements, the r.m.s. anode loading obtained with the series circuit is not quite so good, being $0{\cdot}173I_d$, as compared with $0{\cdot}167I_d$—an increase of 3½ per cent. Nevertheless the series circuit has the great advantage of a relative simplicity in the design of the transformer as a whole, which is comparable only to that obtaining in the case of the double three-phase system of rectification.

CHAPTER VII

THE MERCURY-ARC RECTIFIER IN PRACTICE

From the general account given in Chapter II of the physical phenomena associated with its operation, it will be appreciated that the mercury-arc rectifier consists essentially of a vacuum chamber containing (1) a mercury pool as cathode; (2) several main anodes, whose function it is to carry the power current; and (3) one or more auxiliary anodes for providing ignition and excitation of the rectifier. For small outputs, that is, within the range from 10 to 400 or 500 A, the vacuum chamber or rectifier vessel proper is generally of glass—such rectifiers consequently being referred to as of the *glass-bulb* type. In the case of higher unit outputs, from 800 up to 10 000 or even 16 000 A, the envelope is of steel, for which reason such rectifiers are said to be of the *steel-tank* type.

Field of Application and Characteristic Advantages. The mercury-arc rectifier is akin to an electrical machine of the *series* type, in that its operation is associated with a relatively small voltage drop and, correspondingly, a low internal loss. Consequently, the economy of such rectifier equipment is most pronounced at high direct-current pressures. Furthermore, as the internal loss is occasioned by a voltage drop which is sensibly independent of the load, the efficiency remains high even when the rectifier is operating at reduced output. In fact, it is this latter characteristic which, more than any other operating feature, gives the mercury-arc rectifier its advantage over rotating converting plant.

Both of these features are illustrated by the curves of overall efficiency, i.e. including the associated transformer and essential auxiliaries, given in Fig. 30. It is seen that, at 500 volts, rectifier equipment is already more efficient than rotary converting plant, while considerations of first cost and floor space give it further advantage. At 1 500 volts and above the superiority of the rectifier is very marked. On the other hand, at low load factors and a direct-current pressure as low as 250 volts even, the mercury-arc rectifier still compares favourably with other forms of converting plant. Broadly speaking, the merits of static rectification become prominent in the case

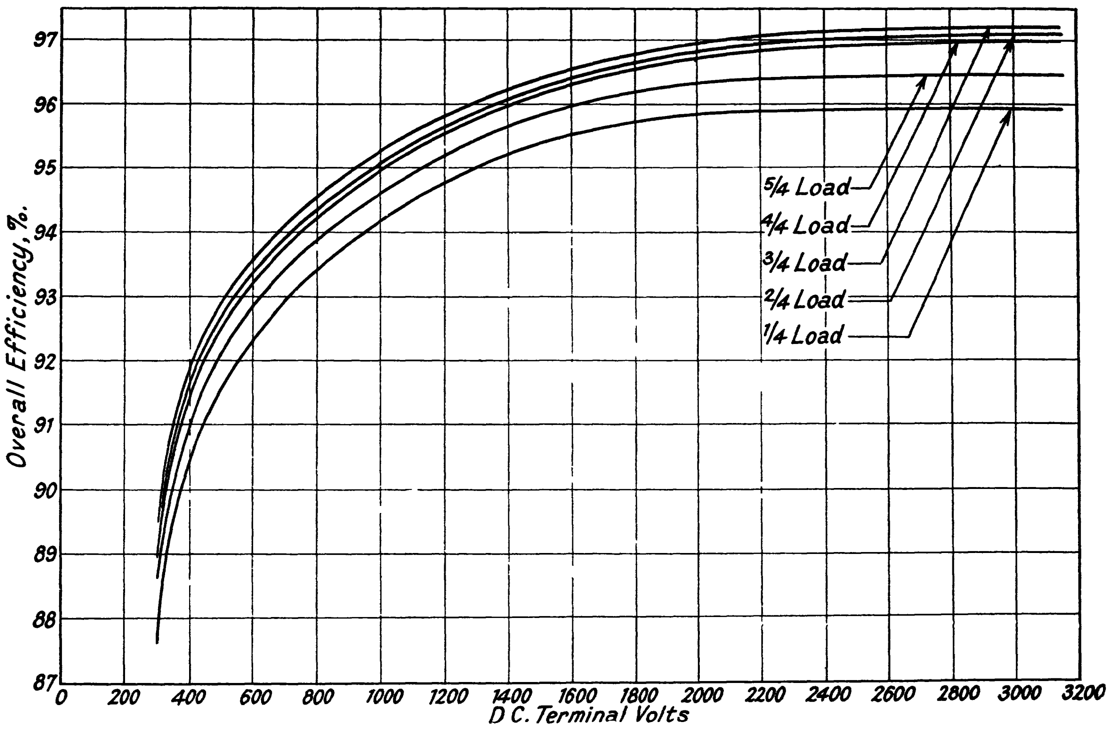

FIG. 30. EFFICIENCY/VOLTAGE CHARACTERISTICS OF MERCURY-ARC RECTIFIER EQUIPMENT

of units handling 100 kW or more at direct-current pressures of 200 volts ~~and upwards~~.

Rectifier units for traction service are in operation up to 3 300 volts, and for broadcasting stations up to 20 000 volts. In the case of the former, where the substation capacity seldom exceeds 2 000 kW, the required energy output can be supplied by a single steel-tank rectifier; or by a bank of glass-bulb rectifiers connected in parallel in cases where the traction system operates at 600 or 1 500 volts. In the case of high-voltage rectifiers, the unit output has so far been limited to about 750 kW, although with the adoption of broadcasting stations requiring 200 kW and more in the aerial system, it seems likely that this limit will soon be exceeded. The largest rectifier so far built is capable of a continuous output of 16 000 A at 500 volts, whilst direct-current pressures of the order of 30 000 ~~volts have already been~~ obtained commercially from a single unit.

The field of application of the mercury-arc rectifier is continually extending; and while the heavy-duty type has special advantages where a direct-current supply is required at high voltage, as in the case of electric railway traction, and for wireless telegraphy and broadcasting purposes, it is ~~being~~ increasingly used also for ~~municipal and industrial~~ power service, and in the electro-chemical, iron and steel, ~~and other~~ special industries. At the same time, the smaller rectifiers are ~~being widely~~ applied to battery charging, and to the supply of direct current for lifts, cranes and hoists, as well as for projection arcs in cinemas and theatres.

The ~~advantages of the~~ mercury-arc rectifier, in comparison with other types of converting plant, may ~~be summarized~~ as follows—

(1.) High and practically constant efficiency at all loads between about 35 per cent and 125 per cent of full load.

(2.) Small no-load losses and consequent high economy at low-load factors.

(3.) Excellent performance at direct-current pressures from about 200 volts up to the highest required for commercial purposes.

(4.) Low maintenance and operating costs—no material is consumed, and there is no wear in the rectifier.

(5.) Negligible depreciation.

(6.) Simple installation—no expensive foundations.

7. Not susceptible to damage by short circuits.
8. No synchronizing needed—and the rectifier is therefore unaffected by disturbances on, or momentary failure of, the alternating-current supply system.
9. High momentary overload capacity.
10. Can be started up in a few seconds.
11. Silent in operation.
12. Easily and cheaply adapted to fully automatic or remote supervisory control.

Glass-bulb Rectifiers. Considering the manifold advantages offered by static means of converting alternating to direct current, progress in the utilization of mercury-arc rectifiers has been relatively slow. The main reason for this has undoubtedly been the prejudice of the engineer against having to depend upon a glass bulb for power service. Also, and quite apart from the fact that glass is a mechanically fragile material, it has often been thought that a glass-bulb rectifier has only a comparatively brief life, at the end of which the bulb burns out and becomes useless—as happens in the case of the household electric lamp.

→ X strong

It is true that ~~glass, considered~~ in relation to normal engineering materials, is relatively fragile; but then a rectifier bulb can readily be protected from mechanical damage. As regards the period of usefulness which may be expected from such a bulb when leaving the hands of the manufacturer, it may be said that convincing evidence is now available as to the longevity of commercial glass-bulb rectifiers. The average expected life of a rectifier bulb may be taken to be not less than 15 000 hours, and it is certainly not less than 12 000 hours. Most rectifier manufacturers guarantee for ~~their bulbs a life~~ of 6 000 hours; whilst some extend this guarantee to the end of the twelve months' maintenance period which is usual to electrical engineering practice in this country. Cases are known where individual rectifier bulbs have been in service for nearly ten years, but such cases are, of course, somewhat rare. At the same time it is worth remembering that of all the rectifier bulbs supplied to date by one well-known manufacturer, 96 per cent are reputed to be still in service.

A typical example of the glass-bulb design of mercury-arc rectifier is illustrated by Fig. 31, which shows the main anodes, the *ignition* anode, and one of the two *excitation* anodes. The mercury vaporized at the surface of the cathode rises in the large condensation chamber or dome forming the major portion of the rectifier bulb and, after condensing in its upper

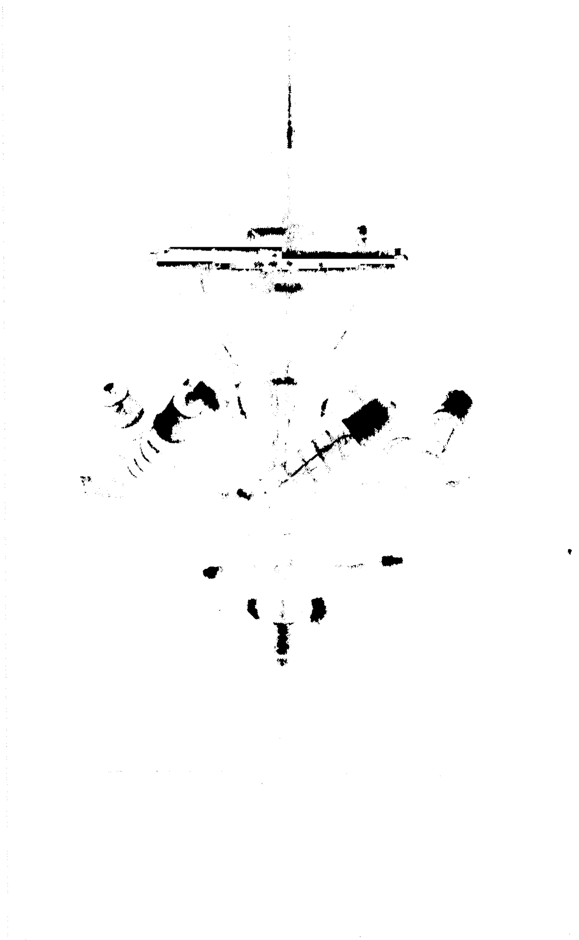

FIG. 31. A TYPICAL GLASS-BULB RECTIFIER
English Electric Co

part, runs down the walls back to the cathode pool at the bottom of the bulb. The length of the main anode arms, which are welded into the walls of the rectifier bulb at the base of the condensing chamber, is determined by the output voltage. Up to about 200 volts the arms are straight and comparatively short, while at direct-current pressures of 500 volts and above they are much longer and contain one or more right-angle bends. The temperature at which the mercury condenses determines the working pressure in the rectifier bulb, and is consequently the vital factor in the design. Moreover, the size of the condensing chamber is determined by the current rating of the rectifier. With increase in the current output, the temperature, and therewith the vapour pressure rises, thus increasing the tendency of the rectifier to *back-fire*.[*] Apart from this factor, however, inherent mechanical weakness of the rectifier bulb has limited the manufacture to sizes capable of direct-current outputs up to about 500 A at 500 volts (continuous rating), when artificially cooled by means of air blown upwards over the surface of the bulb. An example of a 500-A bulb is illustrated in Fig. 32. Higher outputs would seem to be possible by making use of external oil-cooling or by adopting some form of internal water-cooling arrangement.

FIG. 32. A 500-A RECTIFIER BULB
Hewittic Electric Co.

In commercial installations the glass-bulb rectifier and its associated equipment—comprising the ignition and excitation apparatus, motor-driven cooling fan, anode fuses, and other auxiliary fuses—are housed in a substantial sheet-steel cubicle provided with ample ventilation by means of louvres or expanded metal panels, and the individual items of apparatus are so arranged as to be readily accessible. In most cases, especially where the larger units are concerned, the rectifier bulb is mounted in a frame or cradle which is quickly removable from the upper compartment of the cubicle.

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[*] By "back-firing" is understood the sudden failure of the valve action at one or more anodes. Such a condition is tantamount to an internal short-circuit, and its effect may sometimes be destructive in the case of a glass-bulb rectifier. The various causes underlying this phenomenon have been the subject of much research in recent years, and one of the best-known series of investigations has been carried out by von Issendorff. The result of these investigations, which are among the most authoritative available to date, is given in a paper entitled: "The Origin and Mitigation of Back-Fires in Mercury-Arc Rectifiers," and published in *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1930, Vol. 9, pp. 73–114.

Fig. 33 illustrates a double-cubicle rectifier equipment for

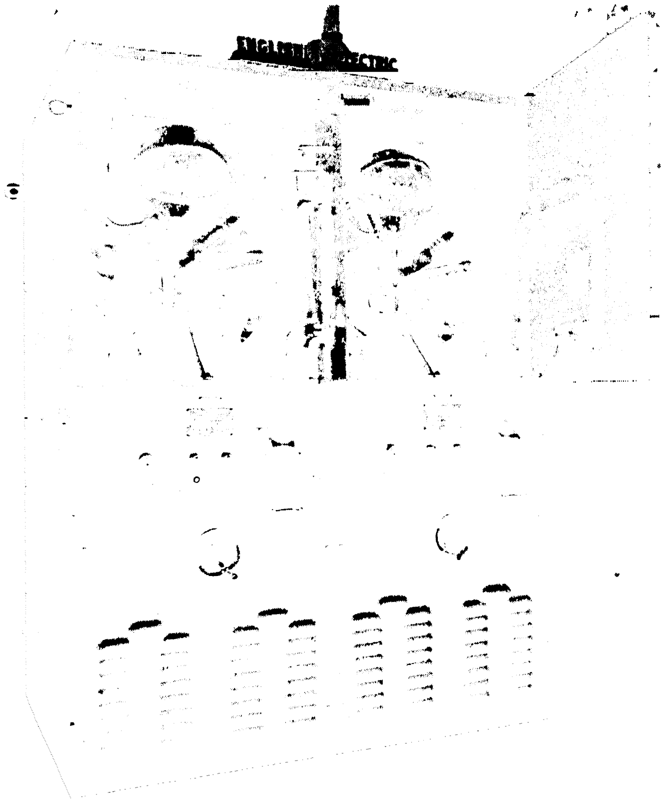

FIG. 33A. DOUBLE-CUBICLE RECTIFIER UNIT
Front view
English Electric Co.

supplying a three-wire direct-current system at 250/500 volts, as manufactured by the English Electric Co., and which in many respects may be regarded as representative of this type of electrical plant. The equipment as a whole is designed on the "unit" principle, each cubicle having its own switchgear, auxiliaries, and fuses. In this way maximum security is obtained, and a number of such units may be run in parallel from a common transformer. Where regulation of the direct-current output voltage is required, the induction regulator or

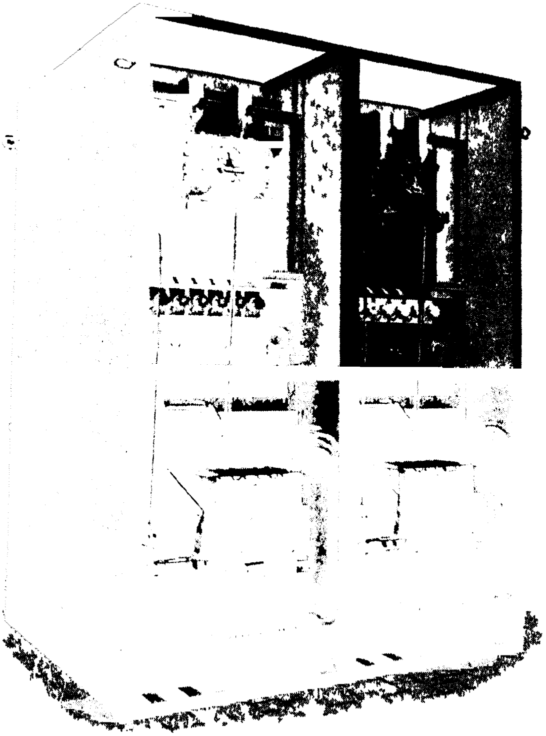

FIG. 33B. DOUBLE CUBICLE RECTIFIER UNIT
Rear view
English Electric Co

grid-control gear may be conveniently arranged on the floor of the cubicle with the operating handwheel on the front panel (Fig. 33A). In such case the smoothing reactor in the output circuit, and the auxiliary apparatus for providing ignition and excitation, are also arranged on the floor of the cubicle, at the back (Fig. 33B). The anode fuses protecting the rectifier unit on the alternating-current side, which have a high rupturing

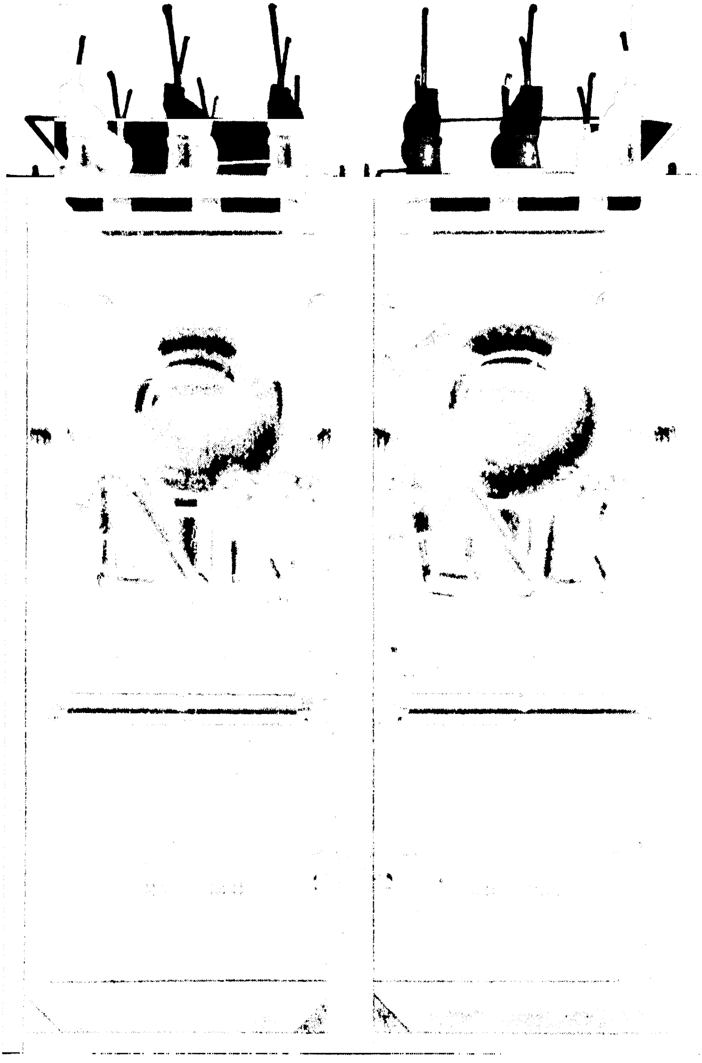

FIG. 34. ARRANGEMENT OF EQUIPMENT IN A RECTIFIER CUBICLE
Bruce-Peebles & Co

capacity and are of the quick-acting type, are then conveniently located at the back of the cubicle, behind the cooling fan with its vertical driving motor. To ensure effective and uniform cooling, the fan is usually surrounded by a shroud which, as in the case of the Bruce-Peebles equipment

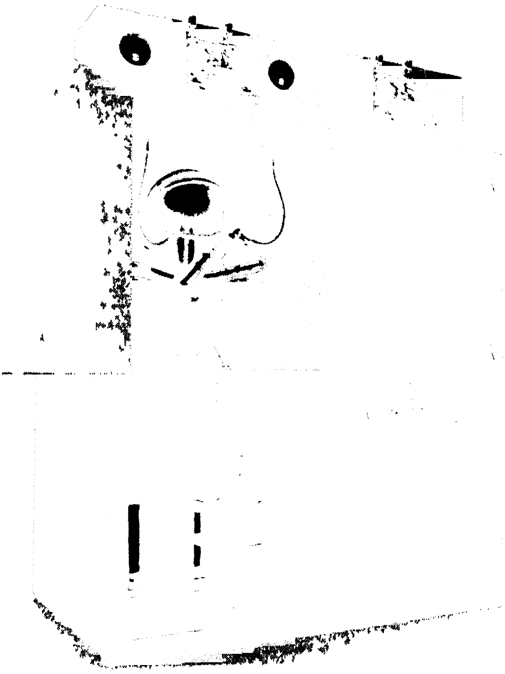

FIG. 35. RECTIFIER CUBICLES WITH DIRECT CURRENT CIRCUIT-BREAKERS MOUNTED ABOVE
English Electric Co.

illustrated in Fig. 34, may take the form of a short length of trunking enveloping the lower part of the rectifier bulb. The direct current circuit-breaker is usually mounted on a panel either at the front of the cubicle and above the bulb compartment, as shown in Fig. 35; or at the back of the cubicle with a drive through to the operating handle on the front panel, as shown in Fig. 33A.

Fig. 35, which illustrates an alternative design of English Electric rectifier equipment, depicts a double-cubicle arrangement for supplying direct current at 220 volts to cranes and hoists. The relays on the front panels serve to bring the second cubicle into service when the first commences to carry more than its normal full load for a given period of time. Unlike the equipment illustrated in Fig. 33, no voltage regulating apparatus is provided. The smoothing reactor can be seen at the back of one of the cubicles, whilst the auxiliary unit for providing ignition and excitation is in this case located at the front.

The main transformer supplying a rectifier unit, or bank of rectifiers, is nearly always placed outside the cubicle and, in some cases, may even be located outside the substation building. Its secondary winding is protected from the voltage surges which frequently arise at light loads under low temperature conditions, e.g. in an unheated substation in the winter months, either by means of surge arrestors of the autovalve type conveniently mounted on the transformer itself; or by horn-gap arrestors mounted on top of the rectifier cubicle (Fig. 34). In addition, the rectifier bulb is generally protected against such voltage surges by special resistance rods of high ohmic value connected between each main anode and cathode.

The methods of establishing ignition and subsequent excitation of the glass-bulb rectifier naturally vary with different manufacturers, but a common circuit arrangement is that employing electromagnetic ignition and single-phase excitation. An example of this type, followed by the English Electric Co., is shown diagrammatically in Fig. 36. The initiation of the cathode-spot in the mercury pool—the operation referred to as *ignition*—is performed by means of a special electrode *S* of light construction, the free end of which normally dips into the mercury cathode *C*. This electrode carries a small armature *N*, which is attracted by an electromagnet *M*, situated immediately above it, as soon as the latter is energized from the secondary winding *T* of an auxiliary transformer. As the ignition electrode is in series with the solenoid of the electromagnet, the ignition circuit is interrupted at the mercury surface when the free end of the electrode is momentarily lifted out of the cathode pool. The spark produced in this way is then immediately transferred, in the form of a small arc, to a pair of auxiliary anodes *E*, which are continuously excited at low voltage—the process referred to as *excitation*—from the transformer winding *T via* the stabilizing resistances *R*. The excitation arc thus established serves to maintain the cathode spot at no-load and very light loads, when the current passing from the main anodes *A* to the cathode *C* falls below the minimum value necessary for keeping up the temperature of the cathode spot. Included in the excitation circuit is the energizing coil *L* of the ignition cut-out relay, whose contacts *P* are in series with the ignition solenoid. As soon as the excitation arc is established, therefore, this relay lifts and permanently interrupts the ignition circuit. An electromagnetically-operated ignition device is also used in Hewittic rectifiers, but the excitation circuit differs slightly from that of Fig. 36 in that excitation anode chokes take the place of the ballast resistances *R*. In the case of Bruce-Peebles rectifiers, the ignition electrode takes the form of a bi-metal strip which bends upwards when heated by the passage of the ignition current.

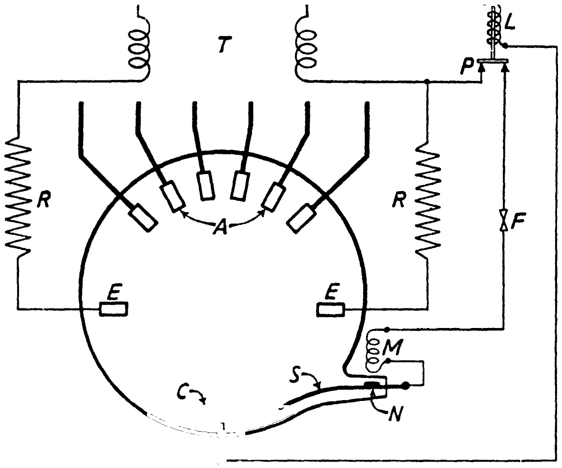

FIG. 36. IGNITION AND EXCITATION CIRCUITS FOR GLASS-BULB RECTIFIERS

English Electric Co.

In cases where the output of the rectifier unit is below about 20 kW, and where the equipment is designed to operate from a low-tension alternating-current supply, it is customary to place the main transformer in the cubicle along with the remainder of the equipment. An example of this arrangement is shown in Fig. 37, illustrating a 40-A 100-volt rectifier unit for supplying the projection arc in the operating room of a small cinema theatre. This particular equipment incorporates a small rectifier bulb requiring no fan to produce forced cooling, so that the cubicle is panelled throughout (with the exception of the door of the bulb compartment) in expanded metal to facilitate the natural ventilation of the equipment.

Steel-tank Rectifiers. It is because of the inherent limitations of the glass-bulb rectifier arising from mechanical weakness of the glass, as well as from difficulties in cooling large bulbs uniformly, that the steel-tank design has been developed for unit outputs in excess of about 500 A, when this type of container commences to be an economic proposition. There are now several makes of steel-tank rectifiers being manufactured in Great Britain, and their construction presents many features common to all. The differences between the various types are largely matters of detail, such as anode construction, the ignition and excitation system vacuum seals, and the arrangements for cooling and condensing the mercury vapour, for example. The general appearance of the steel-tank type of rectifier is clear from the photographs in Figs. 38, 43, and 46, which are representative of modern British practice; whilst the main features distinguishing the several makes will be clear from the sectional drawings in Figs. 39, 44, 45, and 47.

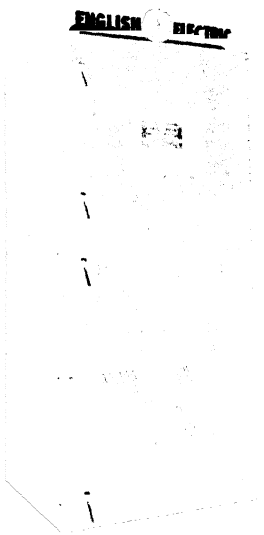

Fig 37A. Rectifier Unit Incorporating Main Transformer in the Cubicle

External view

English Electric Co.

English Electric Rectifier. From the internal arrangement of the English Electric Co.'s 4 000-A* rectifier depicted in Fig. 39, it is seen that, in common with other makes, it has a water jacket surrounding the cathode and the vacuum chamber or rectifier tank proper, from which latter both the anodes and the cathode are carefully insulated so as to prevent any tendency for the current arc to wander to the bottom or sides of the tank In addition, a water jacket covers the central portion of the *anode plate*, as the heavy boiler-plate cover of the vacuum chamber is called; although in the smaller

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* In all cases where the ampere-rating of a rectifier is mentioned, the current output given refers to the *maximum continuous rating.* The *peak* rating is, generally, from two to three times this figure.

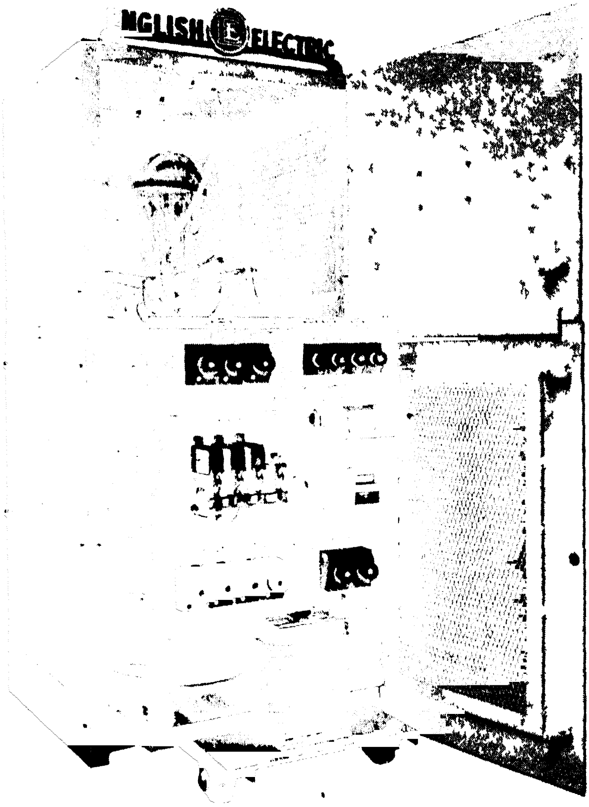

FIG 37B RECTIFIER UNIT INCORPORATING MAIN TRANSFORMER IN THE CUBICLE

View showing withdrawable equipment in lower compartment

English Electric Co

sizes of English Electric Co.'s rectifier this extra cooling-water space is dispensed with. The vacuum tank is constructed of a special quality of sheet iron that has been found to resist the action of mercury vapour and to facilitate the maintenance of a consistently good ~~vacuum. All~~ the seams are ~~carefully~~ welded by normal oxy-acetylene processes to ensure that they are absolutely airtight. The outer casing, seen also in Fig. 38,

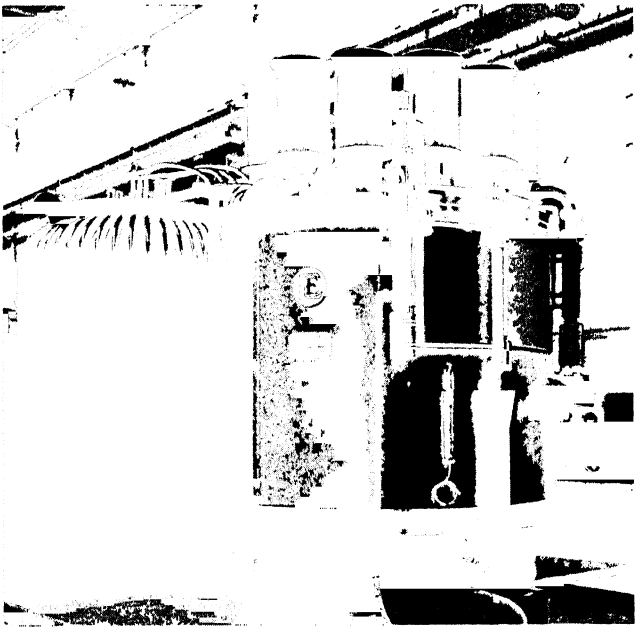

FIG. 38. 4 000-A STEEL-TANK RECTIFIER UNIT
English Electric Co.

is a cylindrical, electrically-welded tank of boiler plate which constitutes the main structural member of the rectifier. It not only supports the vacuum chamber, which is removable as a complete unit without destroying the vacuum (*cf*. Fig. 40), but also carries the accessory equipment required for maintaining and controlling the vacuum. At the base of the vacuum chamber is the cathode, consisting of a steel vessel containing mercury and having a space on its under side for the circulation of cooling water. Any tendency for the arc to leave the

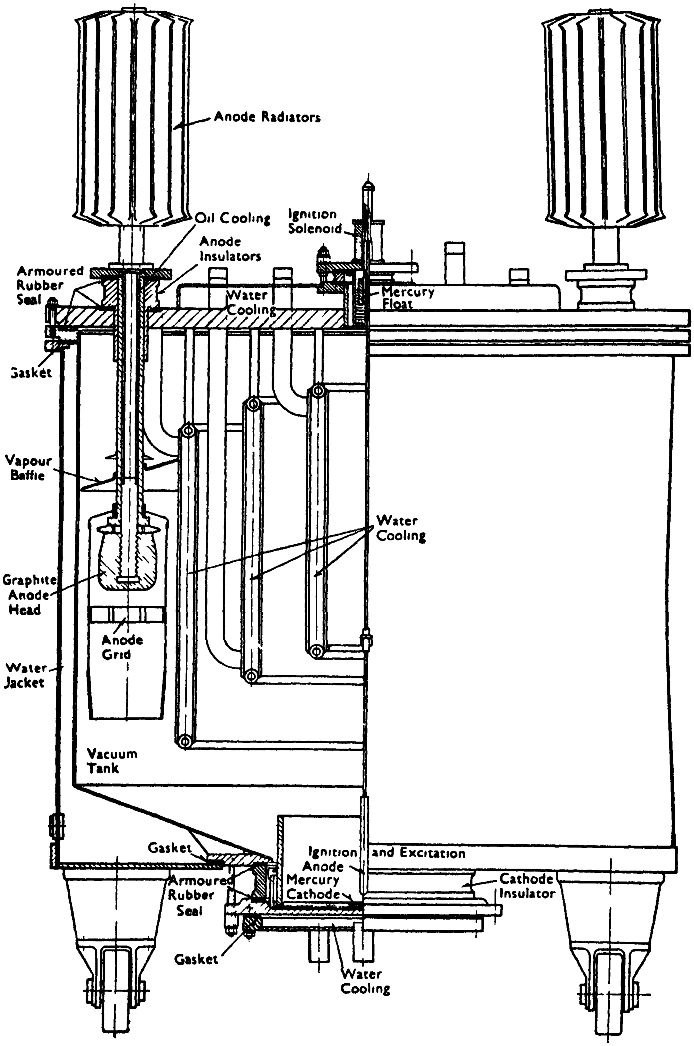

FIG. 39. SECTIONAL ARRANGEMENT OF ENGLISH ELECTRIC STEEL-TANK RECTIFIER

English Electric Co

mercury cathode is prevented by fitting a quartz cylinder of suitable height in the cathode container, which device also serves to protect the porcelain cathode insulator from the heat of the cathode spot.

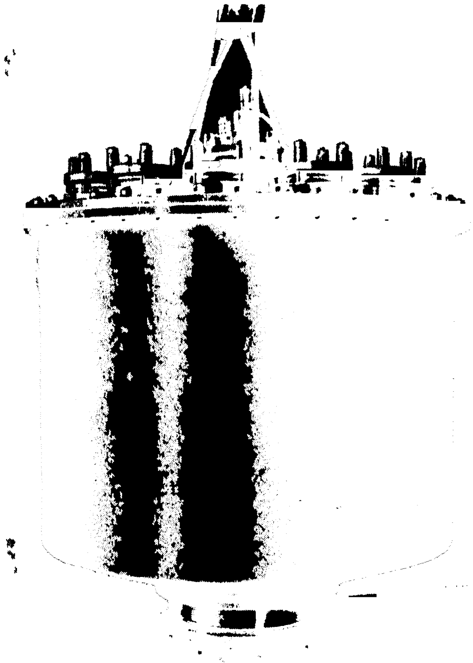

Fig. 40. Vacuum Chamber of English Electric Steel-tank Rectifier
English Electric Co.

The characteristic feature of the English Electric Co.'s design of steel-tank rectifier is the internal water-cooling system, the function of which is to ensure rapid condensation and definite circulation of the mercury vapour generated at the cathode. It consists of a series of concentric cylindrical *coolers* supported from the anode plate and situated in the main vapour space within the ring of anodes (*cf.* Fig. 42). As will be apparent from the diagram (Fig. 41), this special cooling system constitutes a kind of suction pipe above the cathode, whilst its arrangement is such as to provide a definite path of streamlined and non-turbulent flow for the mercury vapour ejected from the cathode, and thus to preclude the danger of back-firing due to clouds of mercury vapour, such as are generated during sudden overloads, finding their way into the arc spaces inside the anode shields.

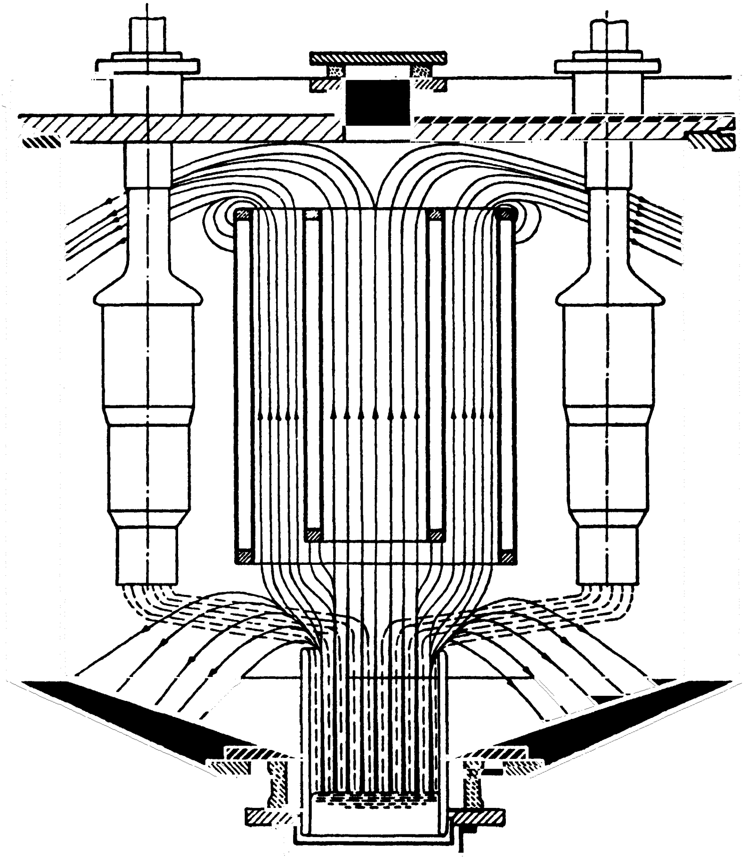

FIG. 41. INTERNAL WATER COOLING SYSTEM OF ENGLISH ELECTRIC STEEL-TANK RECTIFIER

English Electric Co.

The entire anode structure, of which an example is shown in Fig. 42, is designed, as in the case of other makes of rectifier also, from the standpoints of minimizing the occurrence of back-fires and of withstanding the stresses that arise during heavy overloads. To this end graphite anode heads are used, as experience has shown that modern processes of producing electro-graphite furnish an anode material giving the best results, not only as regards freedom from the tendency to cause condensation of the mercury vapour at the anode surface, but also from the point of view of being able to withstand the continually varying thermal stresses that arise. The anode head is screwed on to a solid iron shank, welded to

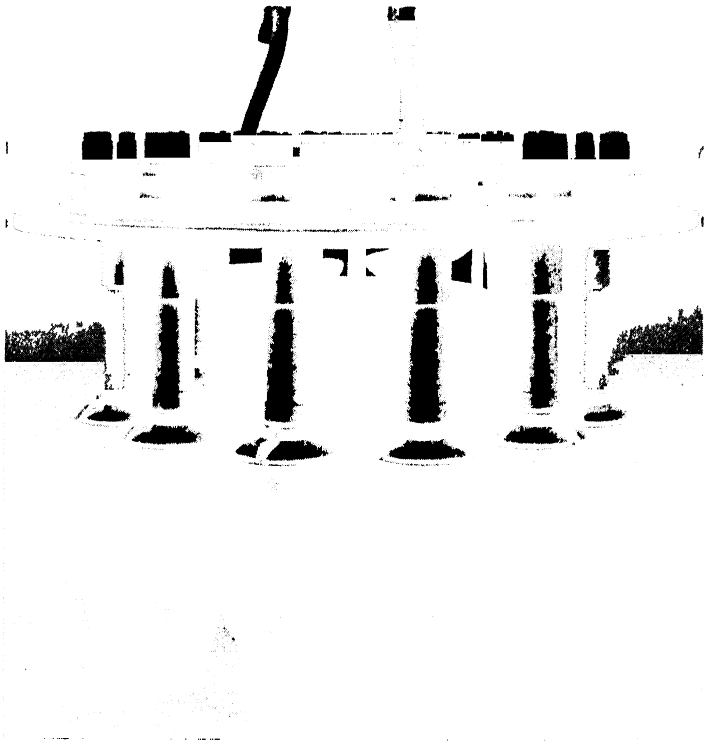

FIG. 42. TOP-PLATE ASSEMBLY OF ENGLISH ELECTRIC STEEL-TANK RECTIFIER

English Electric Co.

a steel tube which passes through an insulator in the anode plate. The upper end of this tubular anode shaft terminates

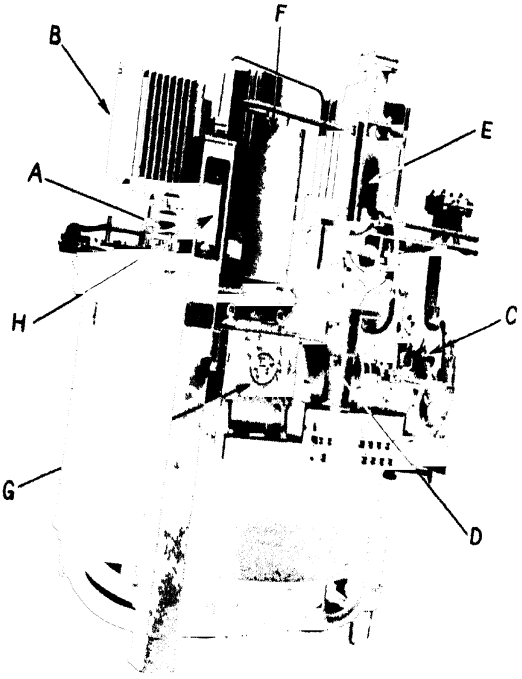

FIG. 43. GENERAL ARRANGEMENT OF A B T H 2 000 A, 600 V RECTIFIER

A = Main anode
B = Water cooled anode radiator
C = Water circulating pump
D = Driving motor
F – Mercury vapour pump
F Inter stage reservoir
G Rotary vacuum pump
H – McLeod vacuum gauge

British Thomson Houston Co

in a flange to which is bolted the oil-cooled anode radiator and the cable terminal The anode stem is insulated down to the head by a porcelain sleeve, and finally by a quartz collar which serves to protect the porcelain from the heat generated at the anode. And in order to prevent condensed mercury from coming into contact with the hot anode, the latter is surrounded by a cylindrical anode sheath of special iron; whilst a deflecting hood or baffle is fitted over all the anodes to direct the condensing mercury towards the walls of the vacuum chamber. The insulated anode sheath also serves to neutralize space charges in the vicinity of the anode, in which function it is assisted by a special metal grid* supported inside the sheath.

BRITISH THOMSON-HOUSTON RECTIFIER. The British Thomson-Houston rectifier, of which Fig. 43 illustrates a recent example, follows similar compact lines of design, with the minor exception that the rectifier unit is supported upon insulating pedestals, instead of upon wheels. The internal arrangement of this type of rectifier is shown in Fig. 44, from which it is seen that a single cooling cylinder is employed for condensing the mercury vapour generated at the cathode, projecting through the anode plate in the form of a dome located inside the ring of anode radiators. These latter are of the water-cooled type and are of very liberal dimensions. This design of rectifier is characterized by its rather shallow and squat vacuum tank, the seams of which are welded by the atomic hydrogen process.

BRUCE-PEEBLES RECTIFIER. In the Bruce-Peebles steel-tank rectifier, illustrated in Fig. 45, it is noteworthy that the internal cooling system is replaced entirely by a high water-cooled dome mounted on the anode plate. In order to guide the rising stream of mercury vapour, two funnel-shaped baffles of sheet-iron are provided, mounted on insulators, above the cathode.

GENERAL ELECTRIC RECTIFIER. The General Electric steel-tank rectifier, shown in Figs. 46 and 47, is again of squat design, and has a wide but shallow cooling dome which provides the means for condensing the mercury vapour issuing from the cathode. In the more recent examples of this design, the equipment for maintaining the rectifier vacuum is secured to the anode plate.

Vacuum Seals. One of the most important details in a steel tank rectifier is the sealing in a thoroughly air-tight and durable manner of the unavoidable joints in the walls of the vacuum chamber as a whole. These comprise the top plate, the main and auxiliary anode inlets, and the opening for the cathode. It is clearly not an easy matter to devise a seal that is both effective and permanent under the influence of a high vacuum and exposure to mercury vapour, and which is at the same time free from material that will exude gases or vapour of any kind. The three main types of vacuum seal employed

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* Not to be confused with the *control grid* additionally provided in the case of grid-controlled steel-tank rectifiers.

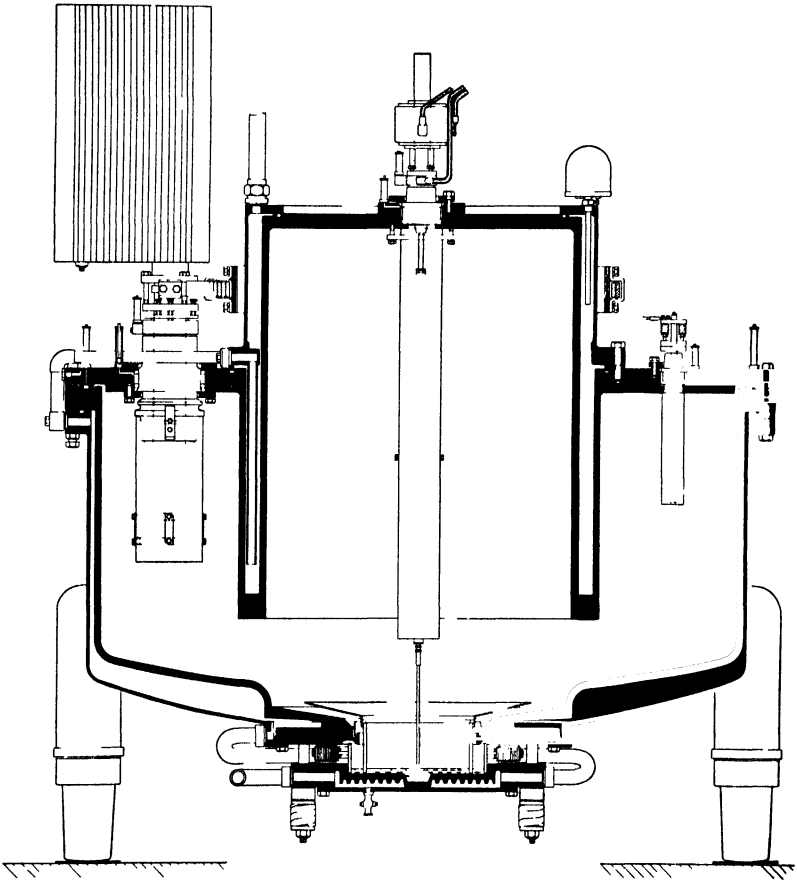


FIG. 44. SECTIONAL ARRANGEMENT OF B.T-H. STEEL-TANK RECTIFIER

British Thomson-Houston Co.

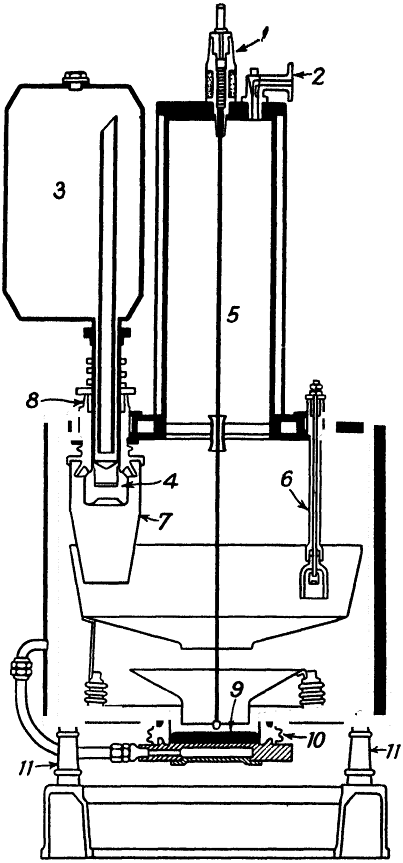


Fig. 45. Sectional Arrangement of Bruce-Peebles Steel-tank Rectifier

1 = Ignition gear
2 = Vacuum cock, connection to vacuum pumps
3 = Anode cooler
4 = Main anode
5 = Ignition rod
6 = Excitation anode
7 = Anode sheath
8 = Anode bushing
9 = Mercury cathode
10 = Cathode insulator
11 = Insulating feet

Bruce-Peebles & Co.

in British rectifier practice are illustrated in Fig. 48 in connection with the sealing of the anode inlets.

The *mercury* seal, shown diagrammatically in Fig. 48 (*a*), comprises an asbestos packing ring *c*, located at the base of

FIG. 46. 2 500-A STEEL-TANK RECTIFIER
General Electric Co

a circular recess in the anode plate *a*, and compressed by spring pressure (not indicated in the diagram) applied to the anode shaft *b*. The packing ring is sealed off from the atmosphere by a layer of mercury *g*, kept in place by means of a rubber washer *e* held by the flange *d*. The sealing mercury is

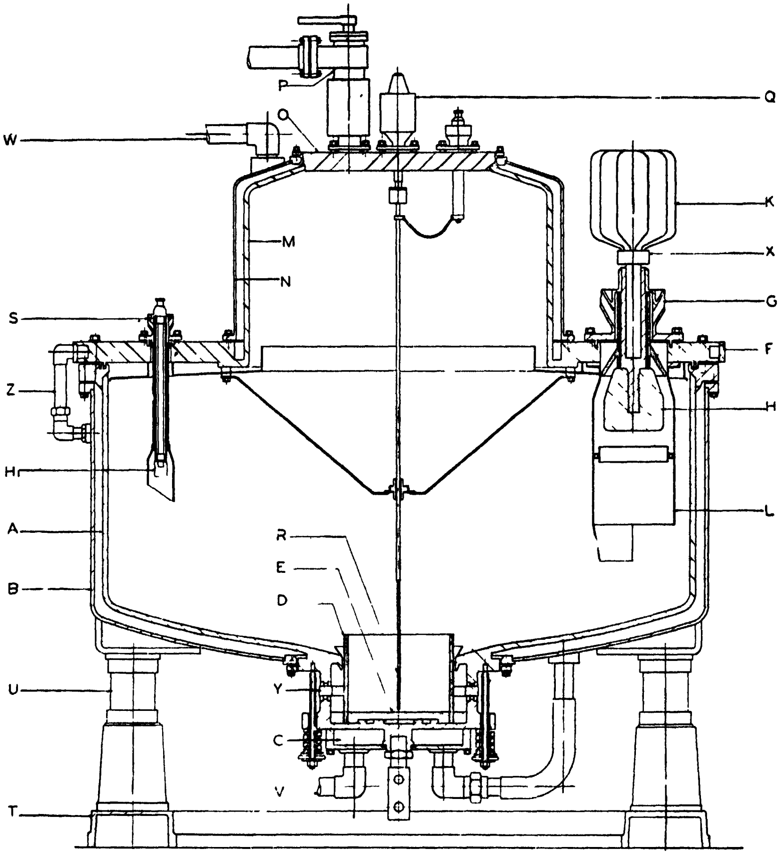
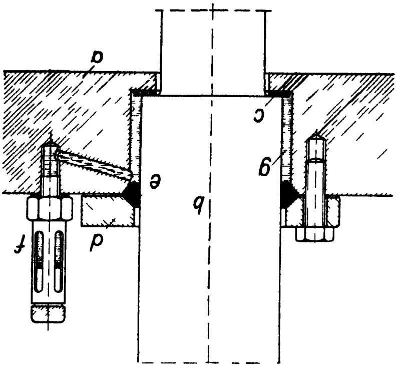


FIG. 47. SECTIONAL ARRANGEMENT OF G.E.C. STEEL-TANK RECTIFIER

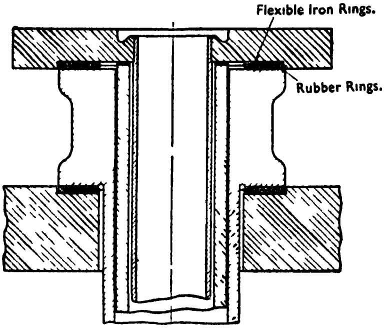
A = Vacuum chamber
B = Water tank
C = Cathode water jacket
D = Quartz cathode shroud
E = Mercury cathode pool
F = Anode plate
G = Vitreous seal
H = Main anode head
H_1 = Auxiliary anode head
K = Anode radiator
L = Anode shield
M = Condensing dome
N = Water jacket

O = Top plate
P = Vacuum cock
Q = Ignition solenoid
R = Ignition anode
S = Auxiliary anode seal
T = Bedplate
U = Supporting insulator
V = Cooling water inlet
W = Cooling water outlet
X = Anode cable socket
Y = Cathode insulator
Z = C.W. connection to anode plate

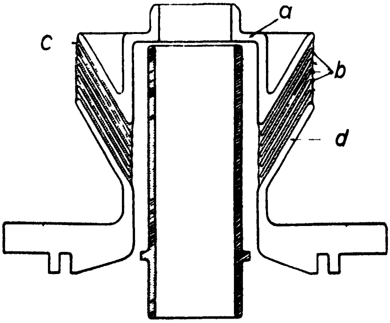
General Electric Co.



(*a*) Mercury seal
Bruce-Peebles & Co.



(*b*) Rubber seal
English Electric Co.



(*c*) Vitreous seal
General Electric Co.

FIG. 48. PRINCIPAL TYPES OF ANODE VACUUM-SEAL EMPLOYED IN STEEL-TANK RECTIFIERS

poured into the gauge-glass *f*, which latter serves to indicate the quality of the seal by the level of the mercury.

The *rubber* seal (Fig. 48 (*b*)) is of a more simple and flexible type. It is, in effect, a wide ring of high quality and specially treated rubber reinforced on the vacuum side—in the same way as a gas-tight joint—by a thin and flexible iron V-ring. By virtue of its simple design, this type of joint greatly facilitates the erection and dismantling of such vacuum connections. It possesses the further advantage of being robust in construction, whilst experience extending over the past twelve years has proved it to be perfectly vacuum-tight.* A more recent seal, also of the permanent type, is the *vitreous* seal depicted in Fig. 48 (*c*). Here a number of thin mild steel cones *b* are held between top and bottom members *a* and *d*. These cones are separately enamelled with a special glass *c*, which has the same coefficient of expansion as mild steel. After assembly of the cones and top and bottom members, the whole is fused up solid in an electrically-heated oven. The result is a mechanically strong unit having, in addition, a very high dielectric strength. This particular seal is employed in connection with an improved metal-to-metal joint—of the tongue-and-groove type—at the surface of the anode plate.

Maintenance and Indication of the Vacuum. No matter how tight the vacuum seals, or how free the rectifier from air leakage, a gradual liberation of occluded gas from the inner surfaces of the vacuum tank is bound to take place during operation. These gases must be continuously removed from the vacuum chamber if the rectifier is to function correctly. The pumping system usually employed for this purpose consists of a high-speed mercury-vapour diffusion pump operating in conjunction with an oil-sealed rotary exhauster. The former gives the necessary high pumping speed at very low pressures, whilst the latter provides the preliminary vacuum for the efficient working of the mercury pump. In some designs of pumping system a barometric seal is incorporated, arranged between the two pumps, which automatically closes off the vacuum tank from the outer atmosphere when the rotary pump is shut down. The general arrangement of such a vacuum pumping system is shown diagrammatically in Fig. 49. In another arrangement

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* The author can recall a case where a 4 000-A rectifier, after standing idle for fifteen months, was found to have lost vacuum to the extent of only 150 microns.

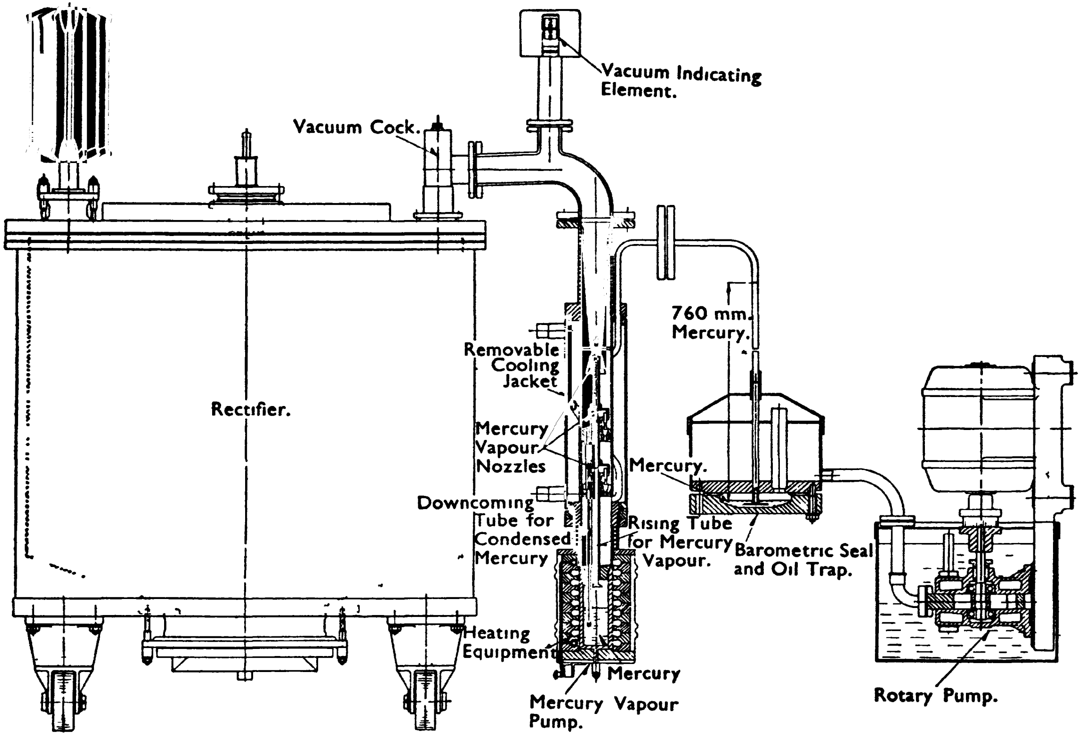

FIG. 49. VACUUM PUMPING SYSTEMS FOR STEEL-TANK RECTIFIERS
English Electric system

an interstage reservoir is provided between the pumps, together with a solenoid-operated non-return valve close to the rotary pump, by means of which it is possible to shut down the latter for a large portion of the working time of the rectifier.

The mercury diffusion pump functions in much the same way as a steam ejector. Mercury is vaporized in a boiler at the bottom of the pump, and in rising and passing through several jets—from two to four, depending on the required pumping capacity—extracts gases from the rectifier *via* the upper part of the pump, after which it condenses and finally returns to the boiler. The mercury-vapour pump shown in Fig. 49 has a boiler surrounded by a resistance-type heating

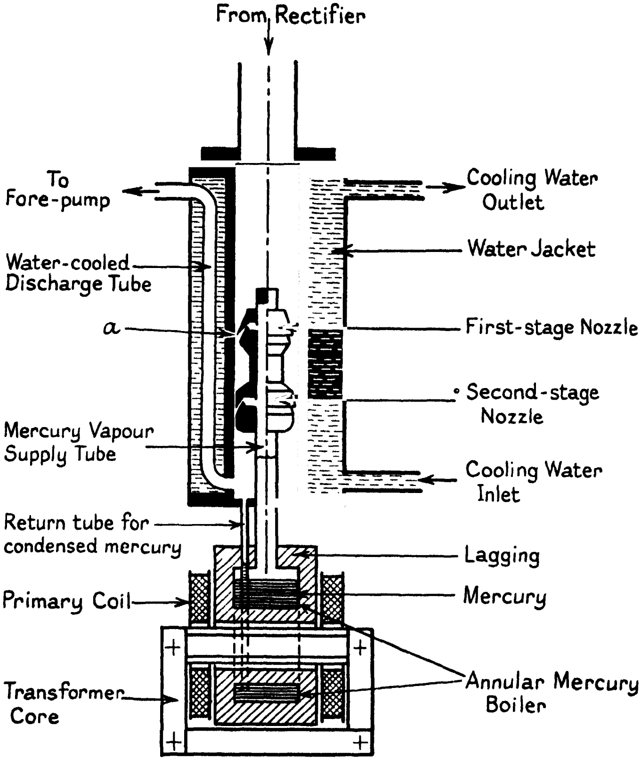

FIG. 50. VACUUM PUMPING SYSTEMS FOR STEEL-TANK RECTIFIERS
British Thomson-Houston diffusion pump

element embedded in ceramic material. In the design of pump illustrated in Fig. 50, an induction type of heating system is used in which the annular mercury boiler acts as the secondary of a small transformer. In this way the heat is generated in the boiler itself, so that the primary winding of the transformer runs quite cool. Fig. 51 illustrates the way in which the mercury level is automatically controlled.

The rotary pump employed as the preliminary vacuum pump is normally of the eccentric disc type, with two impellers sweeping out a crescent-shaped space, the entire unit being immersed in oil and driven either vertically, as in Fig. 49, or horizontally, as in Fig. 43, by a small motor at suitable speed. To enable the vacuum pumping system to be dismantled or examined at any time without destroying the rectifier vacuum, a main valve, which in some cases has a water jacket, is inserted in the outlet from the vacuum chamber. This vacuum valve is usually of mild steel, the conical working

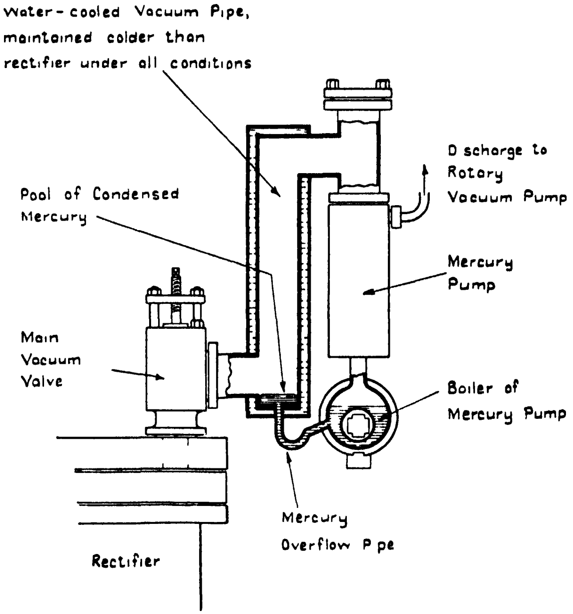
Water-cooled Vacuum Pipe, maintained colder than rectifier under all conditions
Discharge to Rotary Vacuum Pump
Pool of Condensed Mercury
Mercury Pump
Main Vacuum Valve
Boiler of Mercury Pump
Mercury Overflow Pipe
Rectifier

FIG. 51. VACUUM PUMPING SYSTEMS FOR STEEL-TANK RECTIFIERS
Automatic control of mercury level
British Thomson-Houston Co.

surfaces being very carefully ground and polished. To prevent possible leakage to atmosphere, these surfaces are sealed off by a layer of mercury covering the top of the valve.

Indication of the working vacuum in the rectifier is given by a direct-reading gauge of the Pirani type. Various forms of Pirani gauge are employed by different manufacturers, but the working principle is in all cases the same. This system of vacuum indication depends upon the fact that at very low pressures the heat conductivity of a gas increases with pressure, so that the temperature, and consequently the resistance, of an electrically-heated metal filament situated in the gas is a function of the gas pressure. In practice, the metal-filament vacuum detector forms one arm of a Wheatstone bridge, and the galvanometer is calibrated to read directly in microms. The Pirani gauge has the advantage that, being direct reading, it can be used to obtain automatic control of the vacuum through relays and contactors operating on the vacuum pumping system. It has the disadvantage, however, of being unsuitable for indicating the degree of vacuum encountered, for example, during baking-out of the rectifier. In such case, a McLeod compression vacuum gauge* is always employed. McLeod gauges are also used to calibrate and to check the correct reading of Pirani gauges.

Ignition and Excitation Systems. When discussing the physical principles underlying the operation of the mercury-arc rectifier, it was seen that means must be provided for initiating the current arc and for maintaining it at no-load and very light loads. There are two main systems of low-voltage auxiliary supply in use for this purpose—the alternating-current system and the direct-current system.

The single-phase alternating-current system employed in connection with some makes of steel-tank rectifier is shown diagrammatically in Fig. 52. As will be seen, it requires three auxiliary anodes in the rectifier, besides which special cut-out relays are necessary to disconnect the ignition anode and its operating solenoid from the supply as soon as the excitation anodes pick up the auxiliary current arc. Such a

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[*] It would exceed the scope of the present book to describe this type of vacuum gauge, or the different forms of Pirani gauge available commercially. The reader interested in this subject should consult a work dealing with high-vacuum technique, such as *Vacuum Practice*, by L. Dunoyer (Bell & Sons). Incidentally, this book gives a great amount of interesting information on vacuum pumping systems.

single-phase arc is not always so stable that under adverse temperature conditions, for example, the rectifier will deliver very small currents—a fact not infrequently observed in the case of glass-bulb rectifiers. To obtain a really stable excitation arc with the alternating-current system, it is necessary to resort to polyphase excitation. In the case of one make of rectifier, six-phase excitation is employed, and gives stability even with only a voltmeter load. But such systems entail added complication owing to the multiplicity of auxiliary anodes and vacuum seals.

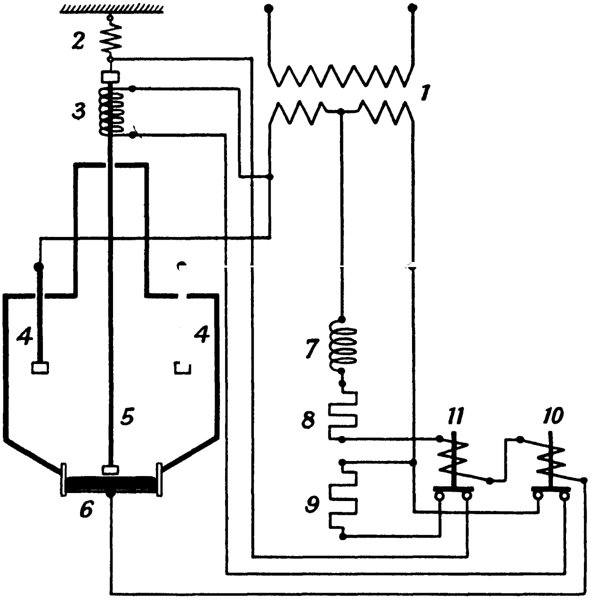

FIG. 52. IGNITION AND EXCITATION SYSTEMS FOR STEEL-TANK RECTIFIERS

Single-phase alternating-current system

1 = Excitation transformer
2 = Return spring
3 = Ignition solenoid
4 = Excitation anodes
5 = Ignition rod and anode
6 = Mercury cathode
7 = Excitation choke coil
8 = Excitation resistance
9 = Ignition resistance
10 and 11 = Ignition relays opening in the order 10–11

Bruce-Peebles & Co.

The direct-current system, of which an example is shown in Fig. 53, has the merit of simplicity in that only one auxiliary anode is necessary. It has the further advantage that the excitation arc, being fed with direct current, is absolutely stable at all loads and temperatures; and that no relays are required to cut off the ignition supply immediately the excitation arc is established. On the other hand, this system has to be operated from a special source of low-voltage direct current—usually from a metal rectifier of the copper-oxide type.

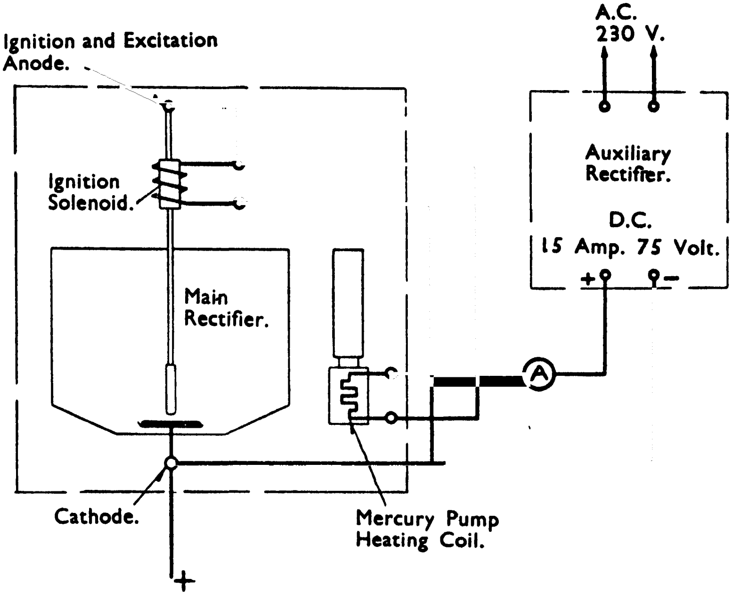

FIG. 53. IGNITION AND EXCITATION SYSTEMS FOR STEEL-TANK RECTIFIERS

Direct-current system

English Electric Co.

Cooling Water Installations. The energy loss in a steel-tank rectifier, manifested by the generation of heat, is dissipated by the cooling water which circulates through the water spaces provided for the purpose. The quantity of water required for cooling depends upon the load, and may be regulated by an automatic inlet valve, in turn operated by a thermostat, giving close regulation with economy in cooling water, and allowing of the accurate temperature adjustment necessary to maintain optimum working conditions.

Where water is scarce or costly, or where it is excessively hard or of a too high electrical conductivity, it is necessary to make use of a closed-circuit cooling system. Pure fresh water, or even distilled water, is then circulated through a re-cooler, which may be either of the air-blast or water-cooled type. Fig. 54 illustrates an air-blast re-cooler forming part of a fully automatic closed-circuit cooling system and capable of dissipating 80 000 B.Th.U. per hour. This particular re-cooling unit circulates some 670 gal. of water per hour, cooling it from 45° C. to 38° C., with an ambient air temperature of 20° C. Automatic control of the re-cooler is effected by a contact-making thermometer connected in the pipe line, by means of which the fan motor is started and stopped at predetermined temperatures of the exit water from the rectifier.

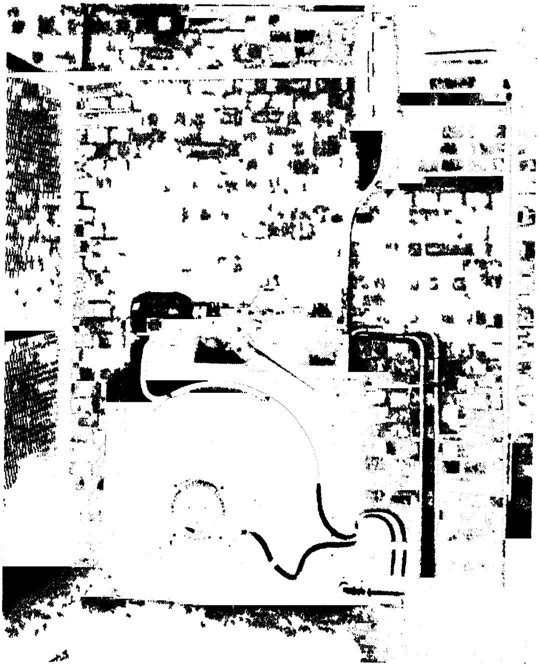

FIG. 54. AIR BLAST RE-COOLER FOR STEEL TANK RECTIFIER
English Electric Co

The cooling water consumption of the mercury-vapour pumps associated with steel-tank rectifiers is very small—generally

Fig 55 Combined Main and Auxiliary Re-cooler Unit
British Thomson-Houston Co.

less than 1 gal. per minute. It is therefore usual to supply their cooling jackets direct from the water main in the substation and to let the effluent water run to waste. In some cases it may be required to provide a closed-circuit system for cooling the mercury pump, or several such pumps in the case of a multi-unit substation. An example of a combined re-cooling installation is illustrated in Fig. 55.

Failure of the cooling water supply to a steel-tank rectifier or its associated mercury-vapour pump may be guarded against by contact-making pressure gauges connected to the appropriate inlet pipes; whilst the chance of overheating, due possibly to a sticking main inlet valve, may be prevented by a temperature relay located in the main cooling jacket surrounding the vacuum tank.

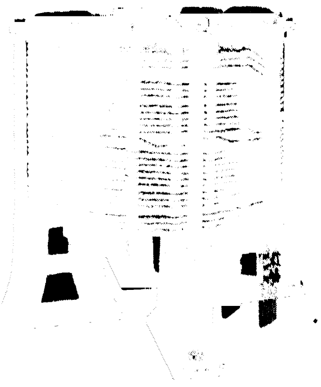

FIG. 56. AIR-CORED SMOOTHING REACTOR
General Electric Co.

Smoothing Equipment. The output voltage of a rectifier is not rectilinear, but contains an alternating-current component or ripple due to harmonics of the supply frequency. The occurrence of this ripple is inherent in the rectification process* and in most cases its presence causes no interference with neighbouring communication circuits, more particularly telephone lines. At the same time, the increasing use of the so-called "all-mains" type of wireless receiving set—a necessarily sensitive piece of electrical apparatus depending on circuit resonance for its correct working—has recently drawn attention to the nuisance which a rectifier substation may be to a residential area supplied from a direct-current network.

The interference experienced in such cases may be of either one or both of two kinds, depending upon whether the source of the electrical disturbance is of high or low frequency. High-frequency interference is due to harmonics of supersonic frequency which are carried by the power current in the mains, and are subsequently re-radiated by the house wiring, to be picked up and demodulated by the receiving set. As the majority of houses are wired either in conduit or lead sheathing, which forms of covering are always earthed and thereby make re-radiation impossible, this form of interference with wireless reception is the less common of the two. Where it does occur, however, it is usually recognizable as a continuous tearing or crackling noise of uncertain pitch—often referred to in the language appropriate to radio as *mush*—rendering broadcast speech and music quite unintelligible. It may be cured at the source by relatively simple and inexpensive means, e.g. by connecting condensers between the anodes and the cathode of the rectifier, and between each direct-current busbar and earth. On the other hand, low-frequency interference, which is due to harmonics of audible frequency carried by the power

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* *Cf.* Chapter XIV.

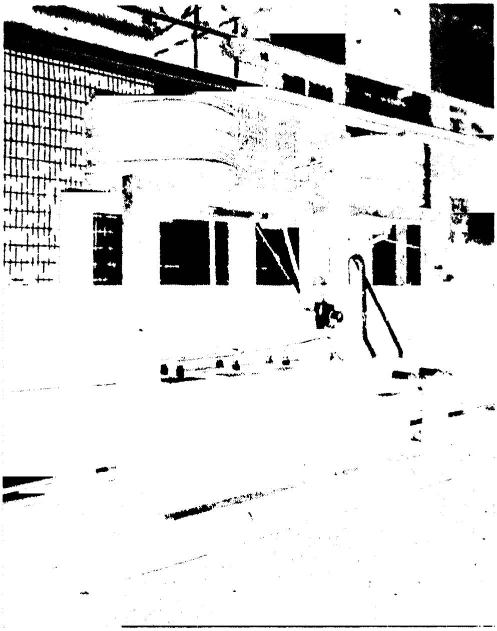

FIG. 57. CONSTRUCTIONAL ARRANGEMENT OF RESONANT SHUNTS
Resonant shunt circuits for 300 and 600 cycles
English Electric Co.

current in the mains and picked up directly by the audio-frequency circuits of the receiving set *via* the cathode heaters, is much more difficult to prevent at the source and its complete cure is often a costly matter. Although perhaps not so objectionable, the distinct hum characteristic of this type of wireless interference is equally persistent and distracting, and its eradication, therefore, just as essential.

FIG. 58 CONSTRUCTIONAL ARRANGEMENT OF RESONANT SHUNTS
Resonant shunt circuits for 300, 600, 900, and 1 200 cycles
British Thomson-Houston Co.

The risk of such interference can be eliminated either by suitable arrangement of the rectifier transformer; or by means of special smoothing equipment comprising a reactor in series with the load together with several resonant shunts, tuned to the predominant harmonics, connected between the positive and negative conductors and on the load side of the series reactor. The series reactor may be of either the iron-cored or air-cored type. The former is perhaps to be preferred as it takes up less space, due to the fact that it may be built after the nature of an oil-immersed self-cooled transformer. The air-cored reactor has the advantage that its inductance does not fall off under overload conditions, as happens with the iron-cored type due to saturation of the core. An example of an air-cored smoothing reactor is illustrated in Fig. 56. The resonant shunts each consist of a low-resistance reactance coil

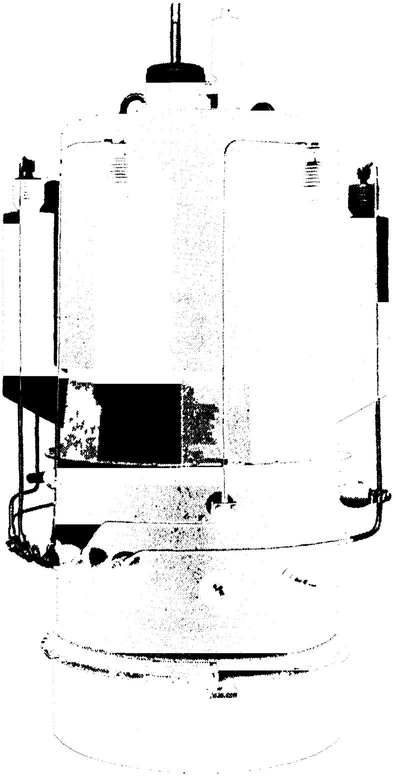

FIG. 59. 500-A. PUMPLESS AIR-COOLED STEEL-CLAD RECTIFIER, SUITABLE FOR CIRCUITS UP TO 800 VOLTS

General Electric Co.

in series with a condenser, and form short-circuiting paths for the several harmonics carried by the direct current flowing through the series reactor. Two examples of resonant shunt construction are shown in Figs. 57 and 58.

The complete smoothing circuit is designed to reduce the harmonics in the output voltage of the rectifier to a degree commensurate with reasonable immunity from interference. It is, naturally, almost impossible to predict beforehand the magnitudes of the individual harmonics, as these depend largely upon the nature of the load on the rectifier, and are also influenced by the reactance conditions on the alternating-current side. But experience has shown that, provided the smoothing equipment reduces the resultant peak ripple to 1½ per cent of the mean value of the output voltage, no interference with communication circuits is likely to result.

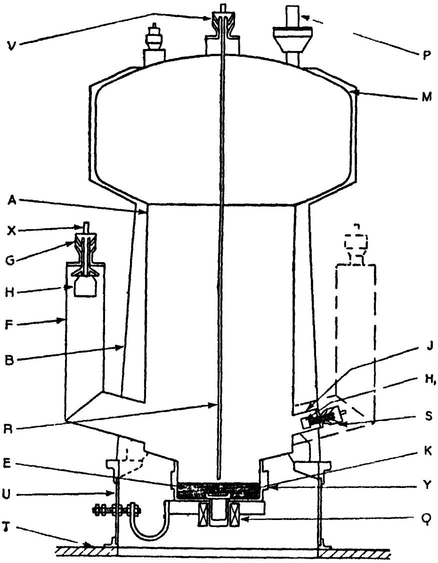

FIG. 60. DIAGRAMMATIC ARRANGEMENT OF PUMPLESS AIR-COOLED STEEL-CLAD RECTIFIER
General Electric Co.

Steel-bulb Rectifiers. The so-called "steel-bulb" type of mercury-arc rectifier—originally developed by Dällenbach*—represents a compromise between the claims of the two preceding types in that it seeks to combine the simplicity of the glass-bulb rectifier with the mechanical strength and the greater current output per unit of the steel-tank rectifier. It is essentially a self-contained, air-cooled, steel-clad rectifying unit whose general construction follows the lines of glass-bulb rectifier design, as may be seen from Fig. 59, which illustrates a 500-A. steel-bulb rectifier suitable for d.c supply at pressures up to 800 volts.

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* *Vide* W. Dallenbach: *Elektrotechnische Zeitschrift*, Vol. 55, 1934, p. 85.

In this particular make of steel-bulb rectifier the vacuum chamber comprises a cylindrical steel tank which is enclosed by a cooling duct forming the main supporting structure of the rectifying unit. Six tubular steel anode arms spring from the base of the vacuum chamber and are carried vertically upwards outside the cooling duct Three short stub arms, also located at the base of the vacuum chamber, carry the excitation anodes; whilst the ignition anode is suspended from the centre of the domed cover (Fig. 60). Ignition of the rectifier is effected by means of an external solenoid, which,

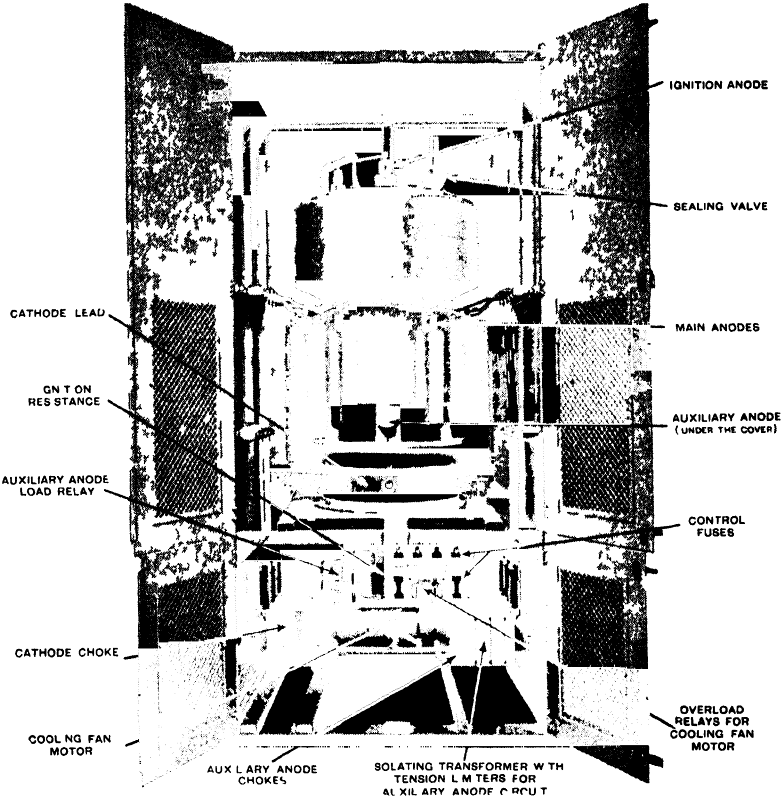

IGNITION ANODE
SEALING VALVE
MAIN ANODES
AUXILIARY ANODE (UNDER THE COVER)
CONTROL FUSES
OVERLOAD RELAYS FOR COOLING FAN MOTOR
CATHODE LEAD
IGNITION RESISTANCE
AUXILIARY ANODE LOAD RELAY
CATHODE CHOKE
COOLING FAN MOTOR
AUXILIARY ANODE CHOKES
ISOLATING TRANSFORMER WITH TENSION LIMITERS FOR AUXILIARY ANODE CIRCUIT

FIG 61 TYPICAL PUMPLESS AIR COOLED RECTIFIER CUBICLE, SHOWING AUXILIARY GEAR ACCOMMODATED IN THE CUBICLE

General Electric Co

upon being energized, causes a small mercury container to break circuit with the ignition anode, which is fixed.

The characteristic feature of the steel-bulb rectifier is the all-steel construction of the complete rectifier envelope (i.e. the vacuum chamber and anode arms). All seams are vacuum-tight welds, except the actual anode joints, which are sealed permanently by the vitreous-enamel process. As the result, the rectifier unit is as durable, from the point of view of maintaining its vacuum, as its glass-bulb prototype. Should it be found that after years of service the vacuum has deteriorated, it can be restored by the use of a portable vacuum-pumping equipment. Unlike the steel-tank rectifier, therefore, the steel-bulb rectifier requires no auxiliary equipment for maintaining the vacuum. It has the further advantage that the optimum working temperature is maintained by air-blast cooling (Fig. 61), so that no closed-circuit water-cooling system, with its attendant temperature-control devices, is required.

The maximum rating so far obtainable with this type of rectifier is 750 A. at d.c. pressures up to 650 volts, although very recent Continental developments seem to indicate that units rated up to 4 000 or 5 000 A. will soon be commercially available.

PART II

CURRENT CONVERSION

CHAPTER VIII

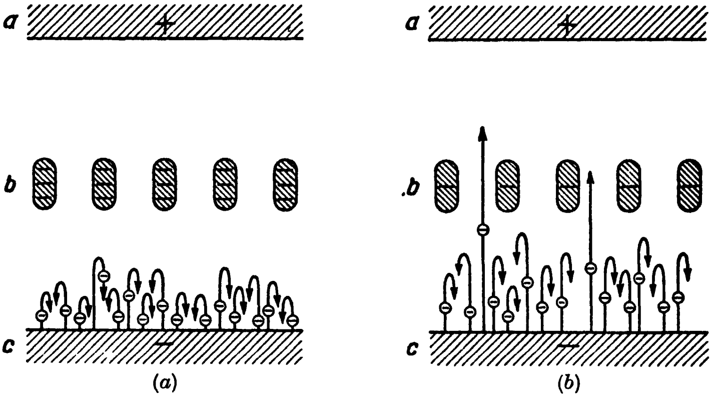
THE PHYSICAL PRINCIPLES UNDERLYING THE CONTROL OF ARC DISCHARGE DEVICES

THE development of the mercury-arc rectifier has been contemporaneous with that of the thermionic valve. And it can only be regarded as a natural outcome of the similarity between these two classes of electric discharge device that attempts should have been made, from the very beginning, to translate to the rectifier those principles and methods of control whose application to the valve has made possible the institution of world-wide services, such as wireless telephony and broadcasting, that have become almost a commonplace in our daily life. These attempts have only recently been crowned with success; but the consequences of that success are of such enormous and far-reaching importance that the development of the mercury-arc rectifier is now entering upon an entirely new phase, and one so novel in its implications that engineering thought is only just beginning to realize its significance and to grasp the fact that yet another revolution in electrical science is in the course of taking place. The exact nature of this revolution—in fact, merely another manifestation of the current tendency, in certain directions, for *electronics* to supersede *electrodynamics*—is perhaps best appreciated by enumerating briefly the many possibilities in the commercial application of rectifier equipment which have been opened up by *grid control*, the term by which this latest development of rectifier research is technically known.

In the first place, grid control of the mercury-arc rectifier enables a regulation of its output voltage to be obtained without the use of extraneous devices, such as the on-load tap-changing transformer or the induction regulator. This characteristic feature of the grid-controlled rectifier is of special importance in the supply of large variable-speed, direct-current motors. Furthermore, grid control renders possible inverted operation of the rectifier, i.e. the *inversion* of direct to alternating current, a property which not only allows of regenerative working in the case of direct-current traction systems, but also lends fresh interest to the transmission of electric ~~power~~ by means of continuous current at very high voltages. In addition, the grid-controlled rectifier affords a ~~simple and~~ efficient means of obtaining alternating currents of high and variable ~~frequency such as are required for the supply of induction furnaces, for~~ example; ~~whilst such equipment~~ can also be made to function as a frequency changer and, in so doing, to con~~vert polyphase current to~~ single-phase current, and *vice versa*. Finally, grid control provides a ready method of using the mercury-arc rectifier for rupturing heavy power circuits in a simple and reliable manner, thus obviating the necessity for circuit-breakers.

Conditions Prior to Arc Ignition. In considering the physical principles underlying the above applications of the grid-controlled rectifier, it is as well to remember that the technique of static apparatus for the handling and control of large powers has in practice been limited to two sub-forms of the electric discharge device or valve *per se*; namely, the vacuum valve in which the electric discharge occurs in space that is essentially free from gas or vapour, and that other type of electric valve in which the discharge takes place in a rarefied gaseous or vapour atmosphere. All such control valves have certain elementary features in common, viz. an incandescent cathode surface which constitutes the source of electron emission, one or more relatively cold anodes to which the electron stream is directed, and a control electrode or *grid* situated in the discharge path between the cathode and each anode. On examining the physical behaviour of these valves, however, we encounter a definite line of demarcation which at once separates the vacuum valve (*electron tube*), or thermionic rectifier, from the vapour valve (*ion tube*), or arc rectifier.

The characteristic operating feature of an electric valve, of whatever type, is that the discharge path continually alternates between a conducting and a non-conducting state. The duration of the former condition is referred to as the *permeable* period, whilst that of the latter is known as the *impermeable* period. Let us consider, in the first place, the conditions obtaining in the valve when it is non-conducting. We will take it for granted that the cathode is at all times able to emit electrons,* and we will assume for the moment that we are dealing with a vacuum valve, so that the discharge space is free from any molecules of gas or vapour (Fig. 62). Electrons in large numbers are then continuously projected from the cathode with a high but somewhat varying velocity. These will travel towards the anode if they come within the influence of an appropriate electric field, such as that created by giving the anode a positive potential; but, if the control grid (Fig. 62 (*a*)) is at a sufficiently high negative potential they will be repelled and driven back into the cathode, this notwithstanding the positive, and therefore attracting, potential of the anode. The reason is that the anode is effectively screened by the control grid, which is specially designed with this object in view. In other words, the flow of current through the valve, constituted by the streaming of electrons from cathode to anode, can be interrupted completely if the repelling influence of the negatively-biased grid exceeds the attracting influence of the positively-charged anode.



(*a*) (*b*)

FIG. 62. THE INFLUENCE OF A CONTROL GRID ON THE TRAVEL OF ELECTRODES FROM CATHODE TO ANODE

(*a*) Strong negative potential
(*b*) Weak negative potential

a = Anode *b* = Control grid *c* = Cathode

Siemens-Schuckert Werke

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* Whether the electron emission arises from the heating of a solid cathode to incandescence by external electrical means (as in thermionic rectifiers and so-called *hot-cathode* types of vapour-arc rectifiers), or from the maintenance of a cathode-spot by the passage of an auxiliary current through the surface of a liquid cathode (as in the mercury-arc rectifier), is quite immaterial to the issue here.

If the negative bias is now reduced somewhat (Fig. 62 (*b*)), but to a value still permitting the net repelling effect of the grid to preponderate over the attracting influence of the anode, only those electrons which are projected from the cathode with a velocity higher than the average will be able to pass through the grid and reach the anode; and as the negative potential applied to the grid is reduced still further, an increasing proportion of the electrons emitted by the cathode will travel towards the anode. For any given positive anode voltage, however, there will always be a large proportion of electrons which can never penetrate the grid, even when its potential is positive; the reason being that, although the effect of the grid, like that of the anode, is to attract the electrons leaving the cathode, the cloud of electrons travelling continuously towards the grid constitutes a negative space-charge which exercises a repelling influence upon the ever-fresh electron stream issuing from the cathode surface. The *saturation current* of the valve is only reached with very high positive values of anode and grid potentials, when all the electrons leaving the cathode are caught by the electric field; its magnitude is determined only by the finite capacity of the cathode for emitting electrons, i.e. by the nature, design, and temperature of the cathode. In the case of the vacuum valve, then, the introduction of a control grid causes the valve to behave like a variable resistance. By altering the potential applied to the grid it is possible to vary directly the magnitude of the current flowing through the valve. The control exercised by the grid is, therefore, continuous; and the transition from the impermeable to the permeable state is consequently not only of a gradual, but also of a reversible nature.

Considering, as before, the discharge path to be in the non-conducting state, let us now observe the effect of introducing a small amount of gas or vapour into such a valve (Fig. 63). Instead of a vacuum of the order of millionths of a millimetre of mercury column, we then have a partial vacuum in the valve, corresponding to a gas or vapour pressure of only a few microns.* If the anode potential is negative, or if, with a given positive anode potential, the control grid has a strongly negative potential bias (Fig. 63 (*a*)), the electrons cannot leave the cathode region. Consequently no current flows through the valve, and the resistance of the discharge path is infinite. At the same time there is no ionization of the innumerable vapour molecules scattered throughout the discharge path, so that the distribution of the electric field is determined solely by the charges at the surfaces of the anode, grid, and cathode, and is unaffected by space-charge considerations.

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* 1 *micron* = 0·001 mm. Hg. There has recently been a tendency on the Continent towards establishing the *tor* (after Toricelli) as a measure of the degree of vacuum, this new unit being defined by 1 tor = 1 mm. Hg.

As the negative potential applied to the grid (Fig. 63(*b*)) is reduced, a few electrons are able to penetrate the grid and reach the anode, as was the case in the vacuum valve; and by virtue of their necessarily high velocity these electrons generate positive ions, by collision with neutral molecules, in the course of their travel through the rarefied vapour atmosphere.* As long as the reduction in negative potential is not too great, the ionization of the discharge path will be comparatively feeble—in the case of mercury-arc discharge devices this condition is represented by currents of a few microamperes only—and these positive ions will therefore have but little influence on the distribution of the electric field throughout the valve. Thus up to this point a gas-filled valve or vapour-arc rectifier can be controlled by a grid in exactly the same way as a vacuum valve or thermionic rectifier. The only difference lies in the degree of control, which is reflected in the curvature of the bottom bend of the anode/grid characteristic† as illustrated

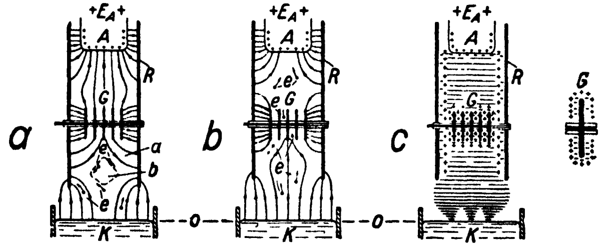

FIG. 63. FIELD DISTRIBUTION IN THE GRID-CONTROLLED RECTIFIER

(*a*) Strong negative grid bias (before ignition)
(*b*) Reduced grid bias (ignition imminent)
(*c*) Strong negative grid bias (after ignition)

Siemens-Schuckert Werke

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* *Cf.* Chapter II.

† Generally referred to as the *mutual* characteristic in literature devoted to the behaviour of wireless valves.

by Fig. 64. In the case of the arc rectifier the curvature is somewhat greater, due to the presence of gas or vapour in the valve. The characteristic can, however, be traversed in both directions up to the point corresponding to the ignition of the arc discharge. In other words, up to this point the control exercised by the grid is both continuous and reversible.*

Ignition of the Arc Discharge. The rapidly increasing steepness of the anode/grid characteristic in the region of feeble current conduction arises from the fact that the positive ions generated in the discharge path create a positive space-charge whose effect on the field distribution near the cathode is equivalent to that of a positive charge on the grid. Under these circumstances the control grid behaves as if its potential were somewhat less negative than it actually is, and it therefore allows a larger number of electrons to pass through it than in the case of the vacuum valve. That is to say, for a given grid potential the valve current will be greater in a vapour-arc rectifier than in a thermionic rectifier.

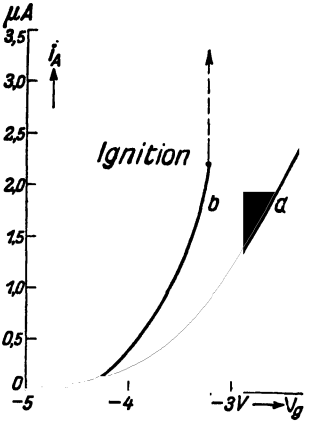

FIG. 64. CONTROL CHARACTERISTICS OF ELECTRIC VALVES

a = Vacuum valve
b = Vapour valve

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The more the negative grid bias is reduced, the greater will be the number of electrons reaching the anode; the greater, also, will be the number of positive ions generated; and thus the more marked will be the action of the resulting positive space-charge in reducing the effectiveness of the grid as a controlling factor in the distribution of the electric field. Eventually a stage is reached where as many positive ions are generated by an electron as will suffice, by adding to the weakening effect of the positive space-charge on the controlling function of the grid, to let another electron pass through the grid to the anode. This essentially unstable condition occurs at a definite value of the grid potential, depending on the design of the valve, and known as the *critical grid potential*. The generation of further positive ions and the liberation of further electrons is now no longer dependent on a further reduction of the negative potential applied to the control grid. Cause and effect—electron flow and ionization—react upon one another to produce a spontaneous and accelerating avalanche of positive ions which at every instant balances and neutralizes the counterflow of electrons emanating from the cathode. The resulting discharge between anode and cathode takes place no longer as a simple flow of electrons but as a combined movement of electrons and positive ions, that is to say, as an *arc discharge.* Accordingly, the transition of the discharge from an electron stream to a current arc (shown in Fig. 64 by the discontinuity in the characteristic) is accompanied by a rush of current which is limited only by the resistance of the circuit external to the valve. The resistance of the discharge path is practically zero.

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* *Cf.* Chapter XIII.

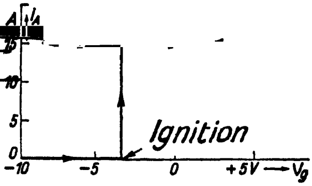

FIG. 65. CONTROL CHARACTERISTICS OF THE ARC DISCHARGE

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The outstanding feature of such an arc discharge is the fact that the *status quo* cannot be restored by reapplying a negative potential to the grid. In the case of the vacuum valve the change from the non-conducting to the conducting state effected by grid control is a continuous and reversible process, but in the case of the vapour-arc valve this change is both discontinuous and irreversible. Once the arc is established between anode and cathode the discharge current is carried equally by electrons and ions, which arrive at the grid at approximately equal rates, so that if a strong negative potential is again applied to the control grid (Fig. 63(*c*)) the decrease in current due to the repulsion of electrons is compensated for by the increase in current due to the attraction of positive ions. The net result, therefore, is *nil*; and the grid thus ceases to have any influence upon the discharge. In effect the presence of innumerable positive ions in the discharge path causes a fundamental alteration in the distribution of the electric field between anode and cathode. The negatively-biased grid attracts these ions, which settle on the grid surface and form a positive layer or sheath there which effectively masks its negative charge. This characteristic operating feature of the grid-controlled arc discharge device is shown diagrammatically in Fig. 65, which may be looked upon as being a continuation of Fig. 64, but drawn to a very much smaller scale.

The relation between critical grid potential and anode voltage for various types of discharge device is illustrated by the ignition characteristics of Fig. 66. Grid-controlled rectifiers of the mercury-arc type exhibit characteristics such as those given by curves 1, 2, and 3. Curve 1 relates to small glass-bulb rectifiers having short anode arms, whilst curve 2 applies to the larger rectifiers of this class having correspondingly longer anode arms. Curve 3 refers to steel-tank rectifiers in which the arc path is, of course, longer still. Curves 4, 5, and 6 represent the ignition characteristics of normal vapour valves

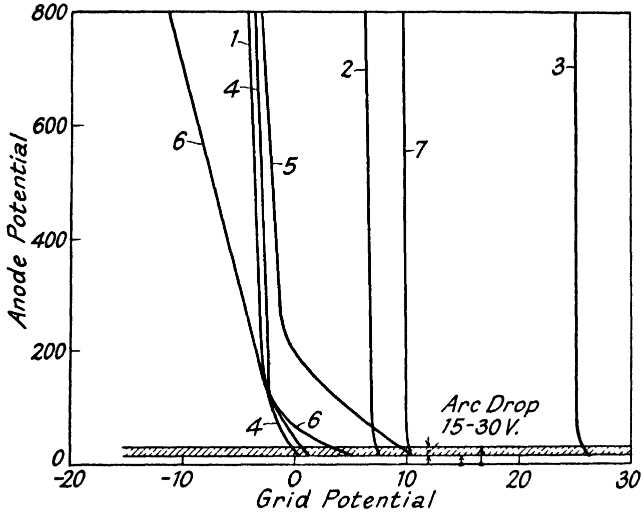

FIG. 66. IGNITION CHARACTERISTICS OF VARIOUS TYPES OF ARC DISCHARGE DEVICE

of the hot-cathode type, in the majority of which the value of grid potential at which ignition of the arc discharge takes place depends considerably on the anode voltage. On the other hand it is possible to construct such valves so that a characteristic like that of curve 7 is obtained.* It is seen from these curves that the *grid-control ratio*, which is defined as the ratio of negative grid voltage-increment to positive anode voltage-increment that will just allow the arc to establish itself (and is thus given by the slope of the ignition characteristic), is seldom constant over the operating voltage range as in the case of vacuum valves,* and may in fact be zero, as shown by curves 2, 3, and 7. It is, moreover, influenced not only by the disposition of the electrodes and by their immediate surroundings, but also by the vapour density in the discharge path. In mercury-arc rectifiers, therefore, the grid-control ratio is dependent on such variable factors as the load on the rectifier, and the local conditions obtaining at the anodes. This fact is of paramount importance in determining the choice of a particular system of grid control, as will be shown later; but it may be mentioned here that the more pronounced this dependence of the grid-control ratio is upon such factors of rectifier operation, the more precise must be the grid-control equipment in determining the correct instant of arc ignition.

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* *Cf.* Chapter XIII.

The grid-controlled rectifier is thus an electric valve or discharge device in which the *starting* of a current arc can be controlled by a grid. Once the arc discharge has commenced, however, the grid has *no further control* over the arc, neither to modulate, limit, nor extinguish it.

Maintenance of the Arc Discharge. After ignition of the arc discharge has taken place the valve is traversed by two streams of electrically-charged particles flowing in opposite directions. The electrons emitted by the cathode travel towards the anode along lines of electrostatic force, while the positive ions wander towards the cathode. Although practically the entire current—over 99 per cent—is carried by the electrons, yet the residual positive ion-stream is a vital factor in maintaining the arc discharge.

As already mentioned, the negative space-charge associated with the pure electron discharge, as occurs in vacuum valves, functions like a negatively-biased control grid in tending to prevent further electrons from reaching the anode. To overcome this repelling influence of the electron cloud over the cathode very high positive anode potentials are necessary. To obtain a current density of 1 A. per sq. cm. in a discharge path 1 cm. long an anode potential of 5 500 volts is required under the most favourable conditions of cathode configuration; whilst if the distance between anode and cathode is increased to 2 cm. the necessary anode potential is as much as 13 800 volts. Such voltage figures do not by any means represent the available e.m.f. in the anode circuit, but are rather the minimum values consistent with maintaining the discharge. That is to say, they actually represent the voltage drop across the valve. It is evident that an internal loss of this magnitude renders such valves useless for the majority of practical applications.

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* In the case of wireless valves, for example, the characteristic valve constant is the *amplification factor*, which is numerically equal to the reciprocal of the grid-control ratio as defined above.

The presence of a gas or vapour in such a valve, resulting as it does in the creation of positive ions, completely changes the conditions under which the discharge takes place. The space between anode and cathode then contains not only the large negative charge of the innumerable electrons, but, with a sufficiently high vapour-pressure (about 1 micron for mercury vapour), almost an equal number of positive ions. In this way the discharge path as a whole takes on a neutral character in spite of the fact that it contains vast numbers of charged particles of both positive and negative character—a condition often referred to as one of *quasineutrality*. Under this condition the negative space-charge effect no longer appears, and consequently the necessity for a high compensating anode potential no longer arises.* Thus by including a small quantity of vapour in the vacuum valve a very considerable reduction in the internal voltage drop is obtained; because the anode potential need then be only just high enough to ensure that the velocity of the electrons leaving the cathode is sufficient to produce ionization of the vapour molecules in the discharge path. This potential, known as the *ionization potential*, is sensibly independent of the vapour-pressure and is about 10 volts for mercury vapour; so that, compared with vacuum valves or thermionic rectifiers, vapour valves or arc rectifiers are characterized by a negligible potential drop across the valve—a fact which leads, in turn, to the occurrence of a much smaller energy loss in this class of discharge device for a given value of discharge current. It is this feature of the arc rectifier which has made it at all possible to handle and control heavy currents by means of static apparatus.

Provided, then, the anode potential remains at a high enough value to effect ionization in the discharge path, the arc discharge will be maintained by the mutual generation of electrons and positive ions. At the same time it is to be remembered, as was pointed out in Chapter II, that the positive ions, being much heavier, travel much more slowly than the electrons; so that during the course of its existence a positive ion is able to neutralize the negative space-charge effect of several hundreds of electrons which it may encounter on its passage from anode to cathode. In other words, to obtain complete neutralization it is sufficient if only one electron out of many hundreds succeeds in ionizing a vapour molecule, and quite small quantities of vapour are thus adequate to achieve this object. It would naturally be wasteful of energy, under these circumstances, to permit the generation of more ions than are actually necessary to provide complete neutralization of the negative space-charge. Such a condition can be avoided as a rule by a suitable choice of both vapour and vapour-pressure. In general, therefore, since the number of electrons reaching the anode which have been generated from neutral molecules in the process of ionization is in the proportion of one to several hundreds—all the other electrons having been generated by the cathode—the discharge current in an arc rectifier is greater than that carried by the electron stream issuing from the cathode.* This surplus is only a fraction of 1 per cent if the ionization of the vapour is just sufficient to produce neutralization of the negative space-charge. But if, as in the case of hot-cathode rectifiers, the cathode is capable of emitting only a definite maximum number of electrons corresponding to the constant temperature of the cathode, *then the discharge current may not exceed the saturation current of the cathode*. Should the external circuit demand a current in excess of the limiting cathode emission, the condition that practically all the electrons reaching the anode emanate from the cathode can no longer be maintained. To augment the discharge current in accordance with the load demand it is necessary that more electrons be generated by further ionization; this increase in ionization manifests itself as an increased energy loss in the rectifier, resulting in excessive positive-ion bombardment of the cathode which, in turn, materially shortens its life. On the other hand, *if the source of electron emission is a cathode-spot in a mercury pool there is no inherent limit to the discharge current*—at any rate the present state of our knowledge leads us to believe that such a source of electron emission is well-nigh inexhaustible.

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* With higher vapour pressures still—of the order of 10 to 100 microns in the case of mercury vapour—it is even possible for a *positive* space-charge to develop in the discharge path. The effect of this is to drag more electrons out of the cathode than are withdrawn due to the positive potential of the anode alone.

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* The deficit is, of course, made good by the stream of positive ions flowing towards the cathode.

Extinction of the Arc Discharge. We have already seen that once the arc has been established, and its subsequent maintenance by external circuit conditions has been assured, the grid can no longer gain control over the distribution of the electric field throughout the discharge path—that is to say, over conditions which determine whether the state of the discharge path is to be conducting or non-conducting. Only when the arc has been extinguished by removing the anode potential, and deionization of the discharge path has taken place, can the grid function again to control the re-establishment of the arc.

Any electric discharge is extinguished when the potential difference between the electrodes is removed, for the electrostatic forces accelerating the electric particles to velocities enabling further charged particles to be generated through the process of ionization by collision, are then made to disappear. At the same time the electrons and positive ions present in the discharge path at the instant in which the circuit e.m.f. is removed tend to remain, and do in fact remain there for a very brief but finite period of time. Thus if the interruption of the potential supply is only momentary, the discharge may continue much as if the e.m.f. had not been removed at all. The time interval required to allow the discharge path to become rid of its charged particles is known as the *deionizing period*, or *time of deionization*, and is a function of the nature of the discharge path as well as of the processes by which deionization takes place. Two means by which the discharge path may be deionized are known to exist. Of these two the recombination of electrons and positive ions, accompanied by mutual neutralization of their electric charges, plays a totally insignificant part in arc rectifiers operating at low vapour-pressures, such as the mercury-arc rectifier. Deionization is almost entirely due to the diffusion of electrons and positive ions to the walls of the discharge path, to which they give up their charge and where they are adsorbed, whereupon mutual neutralization occurs. In grid-controlled mercury-arc rectifiers the time required for deionization is of the order of 10 microseconds, and is seldom more than 100 microseconds. When this time has elapsed the arc is completely extinguished, and the control phenomena previously described reveal themselves anew.

It should be borne in mind, however, that to effect rectification by periodically extinguishing an arc discharge it is not essential that the circuit e.m.f. should be entirely removed, or even made to fall to a value less than the voltage drop of the arc. The same effect can be achieved by reversing the polarity of the e.m.f., so that the anode assumes a potential which is negative with respect to that of the cathode. For then the electric field distribution throughout the discharge path not merely prevents electrons from leaving the cathode surface but actually forces them back into the core of the cathode; thus the electrons can in this case also produce no ionization of the discharge path. The generation of further charged particles ceases in exactly the same way as when the potential difference between anode and cathode is removed. In fact the deionization is even more rapid because the residual ions are not only destroyed by diffusion to, and adsorption at, the walls, but are furthermore neutralized within the zone of the electric field.

The method of arc extinction described above, i.e. by the removal of the circuit e.m.f. or by the reversal of its polarity, is that universally employed in grid-controlled arc rectifying devices. A discharge having once been started by appropriate excitation of the control grid may be allowed to continue until it is extinguished naturally by the reversal of the electrode polarity in the next half-cycle, as in the case of simple rectification of an alternating current; or, on the other hand, it may be forcibly extinguished by the polarity reversal associated with the sudden connecting of a condenser across the electrodes, whereby the instant of arc extinction may be chosen at will, as in the case of certain current-convertor applications. In concluding this brief study of arc control in electric discharge devices it is opportune, therefore, to consider why the imposition of a negative potential on the control grid does not lead to an interruption of the discharge current as occurs in the vacuum valve under the same conditions.

Speaking quite generally, an interruption of the anode current will take place whenever a condition arises whereby a negatively-biased grid succeeds in countering the cathode emission so strongly that electrons are completely prevented from penetrating the grid and thus reaching the anode. As already mentioned, the reason why this condition does not normally arise in mercury-arc current convertors is because the positive ions neutralize the negative charge on the grid in precisely the same way that they neutralize the negative space-charge of the electrons. This is clearly shown in Fig. 67. Consider, for example, an uncharged grid wire of circular cross-section immersed in, and thus completely surrounded by, the arc discharge. In its immediate neighbourhood, as everywhere throughout the discharge path, there are electrons and ions present in very large, and almost equal, numbers. If the grid wire now suddenly receives a large negative charge then the electrons experience a strong repelling force, whilst the positive ions experience an equally strong attracting force. Neglecting the latter effect for the moment, because on account of their inertia the positive ions respond to this force only comparatively slowly, the immediate result of the negative grid-charge is a receding of the electrons from the vicinity of the grid—as occurs in the vacuum valve under the same conditions. But in this case the space from which the electrons have been forced to withdraw is now occupied by positive ions; so that a sheath of ions, or positive space-charge, forms round about the grid wire. The farther away the electrons are compelled to recede from the grid, the greater becomes the positive space-charge between the grid and these electrons, and this space-charge screens the negative grid-charge more and more as its thickness increases. It can be shown* that there is a definite thickness of the positive-ion sheath for which the positive space-charge is exactly equal to the negative charge on the grid, this thickness being further dependent on the positive ion current of the discharge.

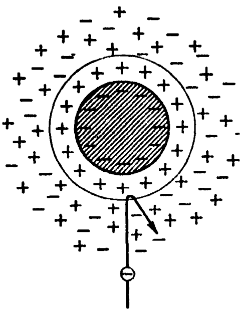

FIG. 67. POSITIVE SPACE-CHARGE SURROUNDING A NEGATIVELY-CHARGED GRID WIRE

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The effect of this sheath is to insulate the grid completely from the discharge. The electrostatic forces of the grid simply cannot reach out into the surrounding space, and there is consequently no tendency for the electrons to recede still further from the grid. Its effective zone of influence becomes wider the less the positive-ion density in the discharge path, i.e. the lower the vapour pressure. If the grid is made more negative still the only result is an increase in thickness of the positive-ion sheath, and therewith a widening of the zone from which electrons are driven away from the grid: outside this enlarged zone the increased negative grid-charge remains just as ineffective.

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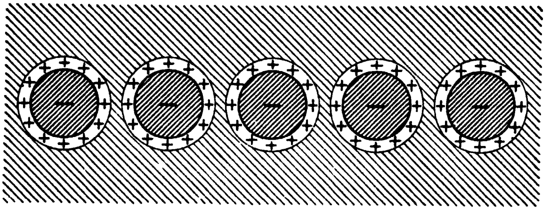
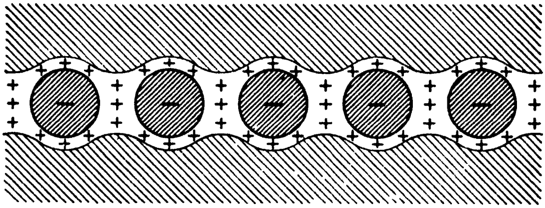
* *Vide* I. Langmuir, *Physical Review*, 1913, Vol. 2, p. 450; and Langmuir and Blodgett, *ibid.* 1923, Vol. 22, pp. 347–356.

Strictly speaking, of course, it is not correct to assume, as we have done up to the present, that the positive ions remain stationary in the space-charge region. Actually, they travel towards the grid under the influence of the electric field and there give up their positive charge. At the same time other positive ions are continuously diffusing from the discharge path as a whole into the space-charge region, replacing those ions which have already reached the grid. On the other hand electrons projected into this region are thrown out again, as depicted in Fig. 67 in the case of one such electron. The condition of a positive-ion sheath surrounding the negatively charged grid, with the consequent screening of the grid-charge, is thus maintained. The only difference as against the previously assumed condition—that of a stationary positive-ion cloud—lies in the fact that we are in actuality concerned with a definite and continuous streaming of positive ions towards the grid; although the magnitude of this stream, as with all positive-ion currents, is a negligible fraction of the discharge current as a whole.

In so far as we have been dealing with the case of an isolated grid wire, all of the above considerations rigidly hold good. But in regarding the behaviour of the grid as a whole we notice an elasticity of the controlling effect which is likely to have a most important bearing on the future of the grid-controlled rectifier. If a negatively-charged grid—and here the term "grid" is used in its widest sense, applying to a mesh of wires or bars, or to a perforated plate or sheath—is inserted in the arc discharge between anode and cathode, two possible conditions of field distribution may arise, as illustrated by Fig. 68. In Fig. 68 (*a*) each grid wire is independently surrounded by a cloud of ions which completely screens it, and the discharge is able to pass between them unimpeded and uninfluenced by the grid. A grid of this type is consequently not in the position to interrupt an arc discharge. On the other hand, in Fig. 68 (*b*) it is assumed that the individual positive-ion sheaths overlap one another, forming a continuous layer from which all electrons are thrown back, as illustrated diagrammatically in Fig. 67. Such a grid *can* lead to the extinction of an arc discharge. It is thus a necessary condition of arc interruption that the several positive-ion sheaths are of sufficient thickness to produce overlapping; i.e. the negative potential applied to the grid must be high and the positive-ion density in the discharge path must be low. Now low positive-ion density means low current density, so that the extinction of an arc by means of a control grid can only succeed under circumstances in which the current density in the arc path is of a fairly low order. The fact that such densities are very much lower than those obtaining in mercury-arc current convertors explains why grid control has been limited, in its application to such apparatus, only to the initiating of the arc discharge,* although it must not be overlooked that in the case of low current densities a negatively-charged grid *can* effect a reduction in the



(*a*) Completely screened grid-charge



(*b*) Partially screened grid-charge

FIG. 68. FIELD DISTRIBUTION IN THE VICINITY OF A NEGATIVELY-BIASED GRID

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* Quite recently it has been found possible to interrupt a continuous-current arc in a mercury-arc rectifier by means of a negatively-charged control grid, but only under somewhat artificial conditions which would seem to restrict its practical application. An account of this revolutionary new development is given in Chapter XIII.

discharge current analogous to that occurring in the vacuum valve—a well-known fact illustrated by the operation of the *ionic amplifier.**

The foregoing phenomena have been admirably summarized by Hull. To quote him—

> The inability of the grid to control or extinguish the arc is due to the formation of a sheath of positive ions about the grid wires, which acts like a layer of insulation. Whatever may be the potential of its inner surface, i.e. the grid, the potential of its outer surface is always that of the discharge. The only effect of making the grid negative is thus to increase the effective diameter of its wires. In other words, a negative wire is equivalent to a slightly larger wire at zero potential. If the thickness of the sheath is small compared to that of the wire, as is usually the case, it is evident that a negative or sheathed grid will not be very different from an unsheathed grid, i.e. an uncharged grid, and hence making a grid negative will not greatly influence the arc. If, on the other hand, the sheaths are made so thick (by reducing the current density) that they touch, thus completely obstructing the arc path, the arc will be extinguished; and if they nearly touch, making the arc path very narrow, the arc may be reduced.

This last is the principle of the continuously-controlled arc upon which depends the operation of the *ionic amplifier*—a type of valve to be described in a subsequent chapter.

In grid-controlled arc rectifiers, then, the discharge is carried equally by electrons and positive ions, and takes place in a rarefied gas or vapour at pressures of the order of thousandths of a millimetre of mercury column. By reason of the absence of any negative space-charge effect, such discharge devices are characterized by low internal voltage drop in conjunction with high current output. In the mercury-arc rectifier, for example, currents of 10 000 to 20 000 A. can be obtained with an arc drop of only 30 or 40 volts.

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(3) M. Steenbeck; *Siemens Zeitschrift*, 1933, Vol. 13, p. 254.

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* Manufactured by Messrs. Siemens & Halske under the name of *wandstromverstärker.*

CHAPTER IX

GRID-CONTROL SYSTEMS AND APPARATUS

THE finality or otherwise of the solutions offered by mercury-arc current convertors to the varied problems in electrical engineering to which such apparatus has been successfully applied depends more on a choice of the grid-control system than upon any other single factor. The method of control employed has not only to be in harmony with the particular application of the current convertor but must, in addition, be in keeping with the conditions under which the equipment has to operate.

General Considerations. In general, the function of any system of grid control is to permit the establishment of a current arc at the anodes of a current convertor at a predetermined instant in the anode voltage-cycle by the application of a positive potential to the individual control grids, and to prevent the re-establishing of the arc at some other instant by the subsequent application of a negative grid bias. The former potential is usually referred to as the *liberating voltage*; whilst the latter is generally known as the *blocking potential*. In the case of mercury-arc current convertors values of liberating potential between 25 and 150 volts are employed in practice, the corresponding blocking potentials varying from about 100 to 300 volts. The values of grid current vary from 10 to 50 mA in glass-bulb rectifiers, and from 200 to 500 mA in steel-tank rectifiers.

The method of controlling a power arc by means of a grid situated in the arc path appears to have been first suggested in 1914 by Langmuir,* who showed how to control the time of starting of the arc in each cycle of anode voltage by the use of a variable grid voltage. The most convenient—one might say the obvious—way of obtaining synchronism between the application of the liberating grid potential and the alternations of the anode voltage is to employ an alternating grid voltage. Assuming this voltage to have a sinusoidal waveform the conditions under which the grid "liberates" the arc discharge may be seen from Fig. 69. From the diagram it is clear that as soon as the instantaneous value of the alternating grid voltage becomes equal to the critical grid potential *g*, ignition of the arc discharge takes place. *The instant in the anode voltage-cycle at which the arc is established thus corresponds to the point of intersection of the grid-excitation curve and the ignition line.* This is the fundamental principle underlying every system of grid control. The inaccuracy of any system employed depends, in practice, upon the degree of freedom of this point of intersection as measured along the time-base of abscissae. If this point can be kept fixed with respect to any time-origin—the instant at which the anode voltage has zero value and is increasing, for example—then the instant in the voltage-cycle at which the arc is established at that particular anode will be invariable in phase.

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* U.S. Patent No. 1,289,823.

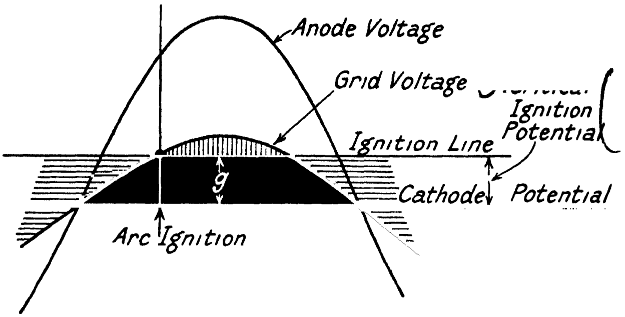

Fig 69. Ignition of the Arc Discharge

As already mentioned in the previous chapter, however, the critical grid potential is not constant in a mercury-arc rectifier, but varies considerably with alterations in the load and with the temperature conditions inside the rectifier. As the result, the ignition line of Fig. 69 is not fixed with reference to the cathode potential, so that the point of intersection of the grid-excitation voltage with the ignition line is variable in its phase position. The consequences of this particular operating feature will be later explained in some detail.

Phase-shift Control. Subsequent to Langmuir's investigations, the study of grid control was taken up in 1922 by Toulon,* who improved the method hitherto employed by applying a sinusoidal voltage to the control grid and varying

U.S. Patent No. 1.654.949.

its phase with respect to the anode voltage. As in all grid-control systems, its *modus operandi* is based on the fundamental principle that the average value of the rectified anode voltage—in other words, the direct-current output voltage from the rectifier—depends on the instant in the positive half-cycle of anode voltage at which ignition of the current arc takes place.

Fig. 70 illustrates three stages in this essentially *phase-shift* method of grid control. Referring to the upper diagram, it is seen that when the grid-excitation voltage is in phase with the anode voltage practically the whole positive half-wave is utilized during rectification, and consequently the rectifier delivers current throughout almost the entire half-cycle. Ignition of the arc takes place at the instant corresponding to $\omega t = \alpha_1$, where $\omega t = 0$ and $\omega t = \pi$ represent the instants in the cycle where the anode voltage $e = (\sqrt{2})E \sin \omega t$ is equal to zero. The angle α by which the arc ignition is delayed beyond the earliest possible instant in the anode voltage-cycle is known as the *ignition angle.* If this angle is increased to the value denoted by α_2 in the middle diagram, the instant of arc ignition is considerably retarded. In this case only part of the available half-wave of anode voltage is utilized during rectification, so that the rectifier delivers current throughout a portion only of the positive half-cycle. The direct-current output voltage from the rectifier, that is, the average value of the useful part of the anode voltage-wave, is consequently reduced in proportion. On still further retarding the instant of arc ignition, corresponding to the ignition angle α_3, a condition is reached in which the grid-excitation voltage is in antiphase with the anode voltage, as shown in the lower diagram of Fig. 70. With such a large relative phase displacement the portion of anode voltage available for rectification is almost *nil*; practically no current is delivered by the rectifier, and the output voltage is very nearly zero.

This particular method of grid control has the great merit of simplicity as regards the apparatus employed to supply the grid excitation. As shown on Fig. 71, the grid-control gear consists only of a small induction regulator, the primary of which is fed from an auxiliary alternating-current supply (which must be in synchronism with the power supply to the rectifier anodes), whilst the secondary is connected to the several control grids through appropriate current-limiting

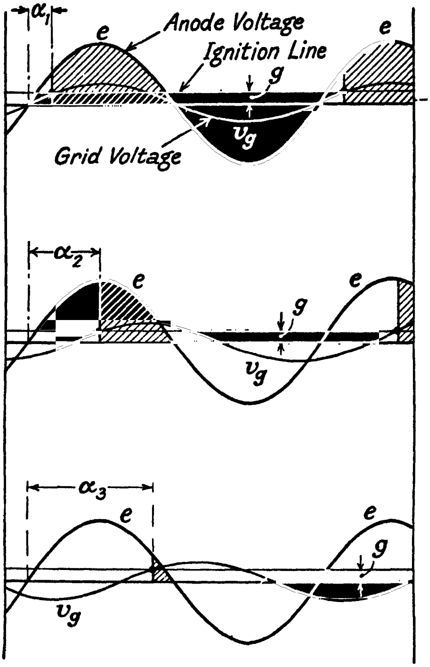

FIG. 70. PHASE-SHIFT CONTROL

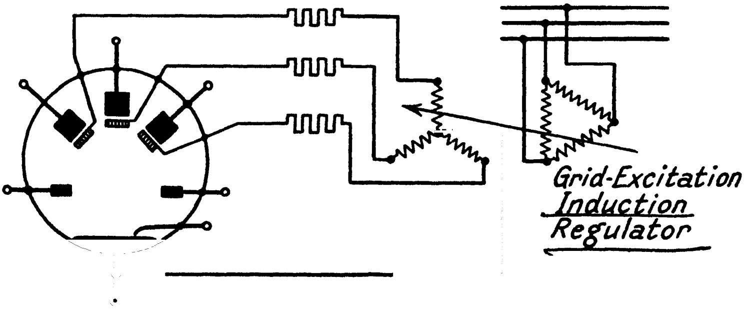

FIG. 71. GRID-EXCITATION SYSTEM FOR PHASE-SHIFT CONTROL

George Newnes Ltd.

resistors. The rating of this special grid-phase regulator is usually less than 100 VA, and the apparatus lends itself readily to fully-automatic or remote supervisory control.

Bias-shift Control. An alternative method of grid control, and one having the same effect as Toulon's method, was developed by Mittag in 1925. With this system the requisite control of the ignition instant is obtained by means of an adjustable bias potential superimposed on the sinusoidal grid-excitation voltage, the relative phase position of which remains unaltered. This *bias-shift* method of grid control is illustrated in Fig. 72. With a positive grid bias, as in the upper diagram, the ignition is fully advanced and the output voltage from the rectifier is a maximum. With zero bias potential on the grid, as shown in the centre diagram, the ignition instant is retarded to the middle of the half-wave of anode voltage, so that voltage delivered at the direct-current terminals of the rectifier is

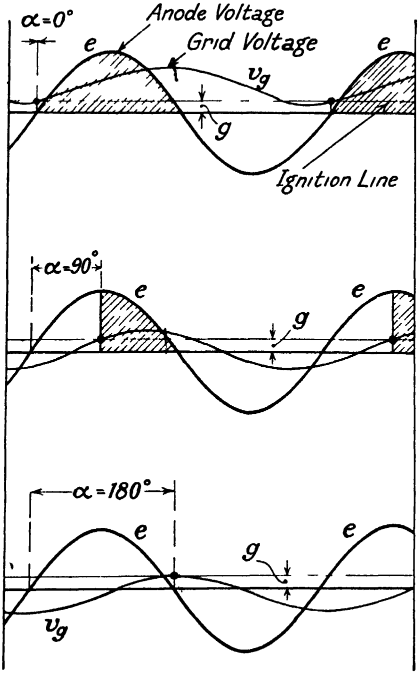

FIG. 72. BIAS-SHIFT CONTROL

reduced to half its normal value; whilst in the case of negative grid bias, as illustrated by the lower diagram of Fig. 72, the ignition is fully retarded, and the rectifier voltage is consequently zero.

Like the phase-shift system, the bias-shift system of grid control also has the merit of simplicity as regards the grid-excitation apparatus. As may be seen from Fig. 73, the grid-control gear consists of a small potential transformer in conjunction with a potentiometer regulator. The moving arm of the potentiometer is connected to the neutral point of the grid excitation transformer, and its position thus determines the potential bias given to the control grids. Here again the rating of the transformer is of the order of a 100 VA, whilst the control potentiometer can readily be adapted to automatic operation.

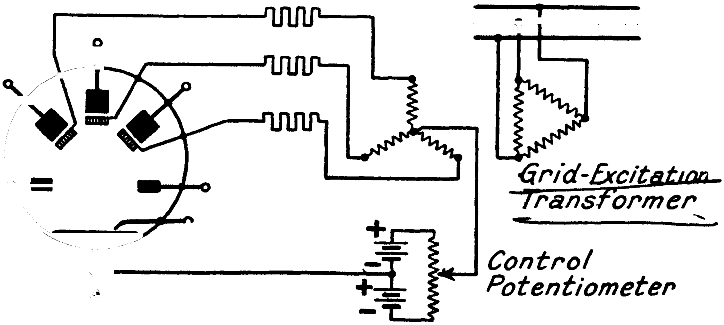

FIG 73. GRID EXCITATION SYSTEM FOR BIAS-SHIFT CONTROL
George Newnes Ltd

Grid-leak Control. An interesting system of grid control developed recently by Messrs. Siemens-Shuckert is that known as *grid-leak* control, by analogy with the demodulation process which takes place in broadcast receiving apparatus employing grid rectification. This system of control makes use of a variable direct-current potential, or inclined potential, on the grid, obtained by charging a condenser through a small rectifier of the metal-oxide type, and allowing the charge to leak away through a resistance whose value can be varied at will. The arrangement is shown in Fig. 74 as applied to one rectifier phase. The corresponding voltage conditions are illustrated by Fig. 75.

The operation of the grid-leak system of control is best understood by considering the limiting conditions determined by zero and infinite values of the grid leak. If its value is infinite, then the condenser *C* will be charged up to the maximum negative value of the secondary phase-potential of the rectifier transformer, since the inclusion of the metal rectifier *V* prevents the flow of charging current during the positive half-cycle of anode voltage. The control grid, being connected to the condenser, thus attains the same negative potential, which is maintained indefinitely if the losses in the grid circuit be neglected. On the other hand, if the value of the grid leak *R* is zero, so that the metal rectifier is virtually short-circuited, the condenser has applied to it the alternating anode voltage. Consequently the potential of the grid is at all instants the same as that of the corresponding anode.

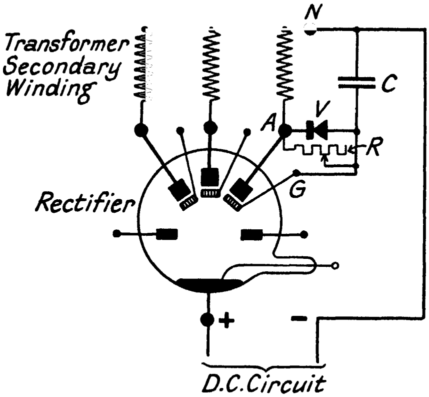

FIG. 74. GRID-LEAK SYSTEM OF GRID CONTROL

These two conditions of grid voltage are indicated by $R = \infty$ and $R = 0$ in Fig. 75. For grid-leak values between these limits, the grid potential rises from its initial negative value more or less slowly according as to whether *R* is small or large. The point of intersection of the inclined grid-potential line with the ignition line can thus be varied by regulating the value of the grid leak *R*. In Fig. 75, three such points of intersection *a*, *b*, and *c*, are shown corresponding to the ignition angles α_1, α_2 and α_3. By a suitable choice of values for *C* and *R* the time constant of the grid circuit can be varied, and the inclination of the grid-potential line altered, so that the entire range of intersections from a to d can be obtained as with the two previous methods of grid control.

Merits of Impulse Control. All the foregoing systems of grid control suffer from the common disadvantage that they do not permit of very exact determination of the ignition instant.

This drawback is accounted for by the fact that, in a mercury-arc rectifier equipped with control grids, the critical ignition voltage is not constant, but varies with the load and also with the temperature conditions inside the rectifier. As the result, the ignition line of Figs. 70 and 72 is not fixed with reference to the cathode potential. And hence for a given degree of grid control, i.e. for a given ignition angle, the point of intersection of the grid-excitation voltage with the ignition line is variable in its phase position.

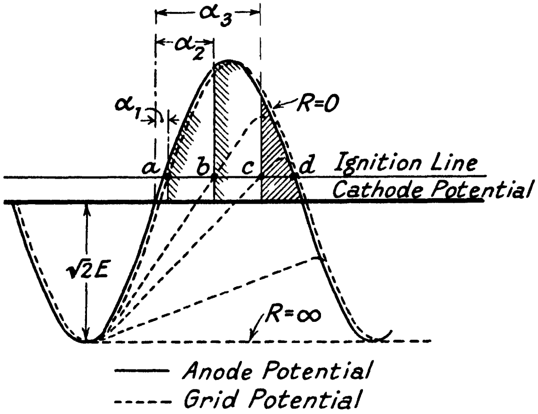

FIG. 75. VARIATION OF IGNITION ANGLE α WITH DIFFERENT VALUES OF GRID-LEAK RESISTANCE R

This unwanted feature is illustrated by Fig. 76, from which it is seen that quite an appreciable variation in the direct-current voltage may arise without any alteration having taken place in the setting of the grid-control apparatus. In the diagram the ignition line XX, corresponding to the critical grid voltage g at full load, is intersected by the grid-excitation voltage at the point A which, in turn, corresponds to the ignition angle α, determined by the setting of the grid-control gear.

Under these conditions the rectified portion of the anode voltage wave is represented by the area MNP; whilst the voltage obtained from the rectifier, being the mean value of this area over the period T, is represented by V. If the rectifier is subjected to an overload, for example, the critical grid voltage increases to a value g', for which the corresponding ignition line is $X'X'$. The point of intersection with the grid-excitation voltage now occurs at the point B, for which the corresponding ignition angle is α'. Under this overload condition, then, the rectified voltage is represented by the reduced area QRP, giving a reduced output voltage, represented by V'.

The net loss in output voltage due to the change in ignition angle from α to α' is thus represented by the mean value of the area $MNRQ$ over the period T, and may amount to as much as 5 per cent in certain cases. And as this loss occurs over and above the natural drop in voltage, due to the falling regulation characteristic of the rectifier unit as a whole, it is clear that methods of grid control in which the ignition line is intersected obliquely by the grid-excitation voltage are of little value where close voltage regulation is required.

In the majority of practical applications for grid-controlled rectifier equipment it is of paramount importance that the instant in the anode-voltage cycle in which the current arc is established should be precisely defined. Such precision can only be attained by potential impulses, and modern practice in the use of grid control would seem almost universally to have accepted this principle. Such methods of control consist in maintaining the grids normally at a negative potential, thereby preventing the establishment of the current arc, and in applying momentarily a positive potential to each grid in succession. [redacted] Fig. 77, grid-control systems of this kind are not susceptible to the voltage error described above with reference to Fig. 76; the reason being that the grid-excitation voltage intersects the ignition line practically at right angles, so that any variation in the critical grid voltage has no sensible effect on the ignition angle.

Variation of the rectified voltage, and thus of the power output from the rectifier, is obtained by altering the phase relationship of the potential impulses with respect to their corresponding anode voltages. The conditions obtaining in the case of a six-phase grid-controlled rectifier under these circumstances may be understood by reference to Fig. 78. The average value of the rectified voltage depends upon the instant in the positive half-cycle of anode voltage at which the current arc commutates from one anode to the next. The later the instant, the lower is the average value—in other words, the voltage V delivered at the direct-current terminals of the rectifier decreases with increase in the ignition angle α.

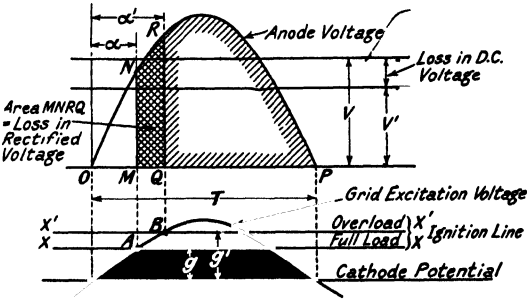

FIG. 76. VOLTAGE ERROR OCCURRING WITH SINUSOIDAL GRID-EXCITATION

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The diagrams in Fig. 78 show the theoretical wave-forms of rectified voltage corresponding to a pure resistance load. In practice the resultant curves are considerably smoothed out by the inductance of the direct-current load circuit, and with the aid of suitable smoothing equipment the output voltage can be made as devoid of harmonic ripple as in the case of rotating converting plant, as may be seen from the oscillograms in Fig. 79, which relate to a 300-volt rectifier unit.

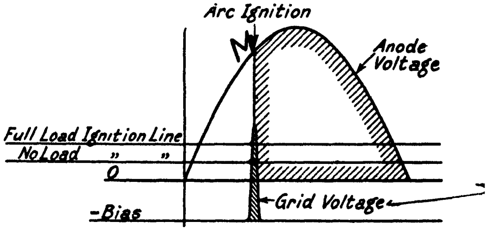


FIG. 77. MODE OF OPERATION OF IMPULSE GRID-EXCITATION SYSTEMS

George Newnes Ltd.

Impulse Control Systems. The potential impulses applied to the grids are usually derived either from a source of direct current in conjunction with a potential dividing arrangement and a synchronously-driven distributor (Fig. 80), or from a special "impulse generator," i.e. a small alternator delivering a polyphase voltage having a peaked wave-form. Where a distributor is employed, and only manual control of the output voltage is desired, the requisite phase displacement of the potential impulses is obtained by adjusting the angular position of the disc supporting the distributor segments.

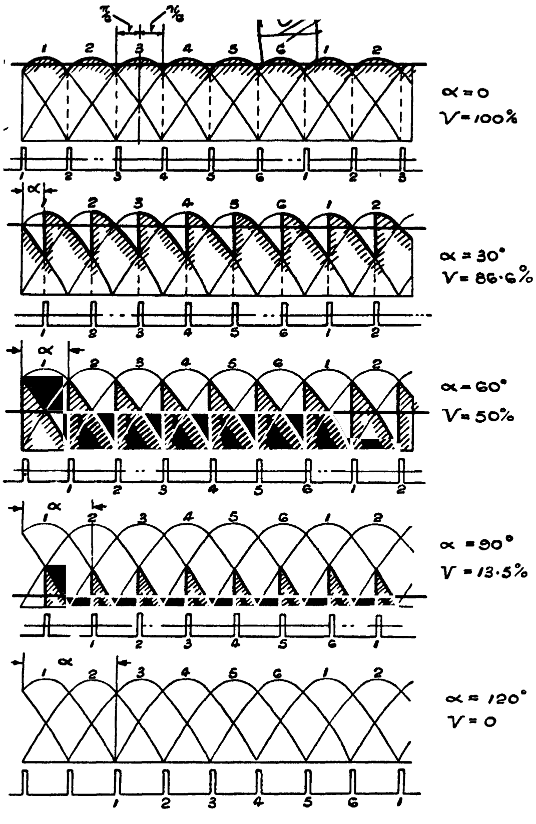
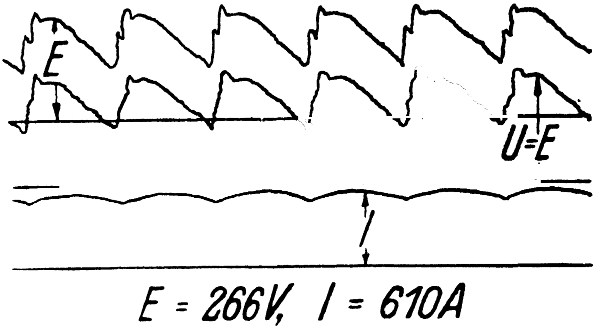
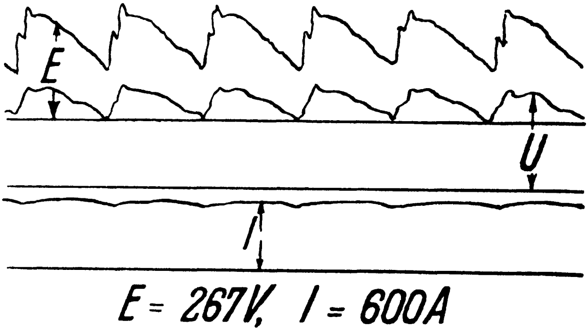


FIG. 78. VARIATION OF THE OUTPUT VOLTAGE WITH THE PHASE-ANGLE OF ARC COMMUTATION

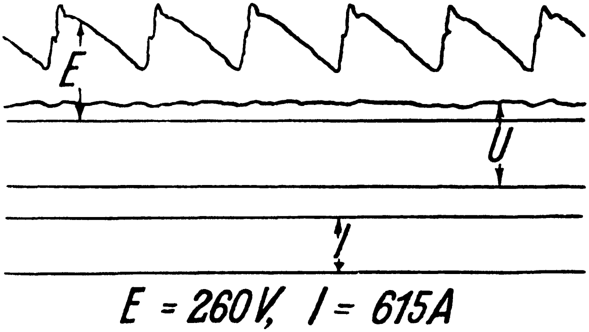
English Electric Co.



(*a*) Without smoothing equipment



(*b*) With series reactor only



(*c*) With series reactor and resonant shunts

FIG. 79. OSCILLOGRAMS SHOWING EFFECT OF GRID CONTROL ON OUTPUT OF 300-VOLT RECTIFIER WHEN OPERATING AT REDUCED VOLTAGE

E = Rectifier terminal voltage
U = Direct-current busbar voltage
I = Direct-current output

English Electric Co.

In the case of fully-automatic or remote-supervisory voltage control, the angular position of the disc is adjusted by means of a small motor operating through worm-gearing and a chain drive. A grid-control unit of the latter type, as manufactured by the English Electric Co., is illustrated in Fig. 81. Where use is made instead of a "peaky-voltage" alternator for obtaining the grid-excitation supply, the field system of the synchronous driving motor is brought out to slip-rings, the brushes of which are connected to a special phase-shifting regulator. This arrangement is sometimes adopted also in the case of the distributor type of grid-control apparatus, as it is purely electrical and, therefore, instantaneous in operation. The requisite variation of the ignition angle is obtained by shifting the effective magnetic axis of the synchronous motor relative to the centre-line of the poles of the rotor. To this end the field system of the motor consists of two windings situated at right

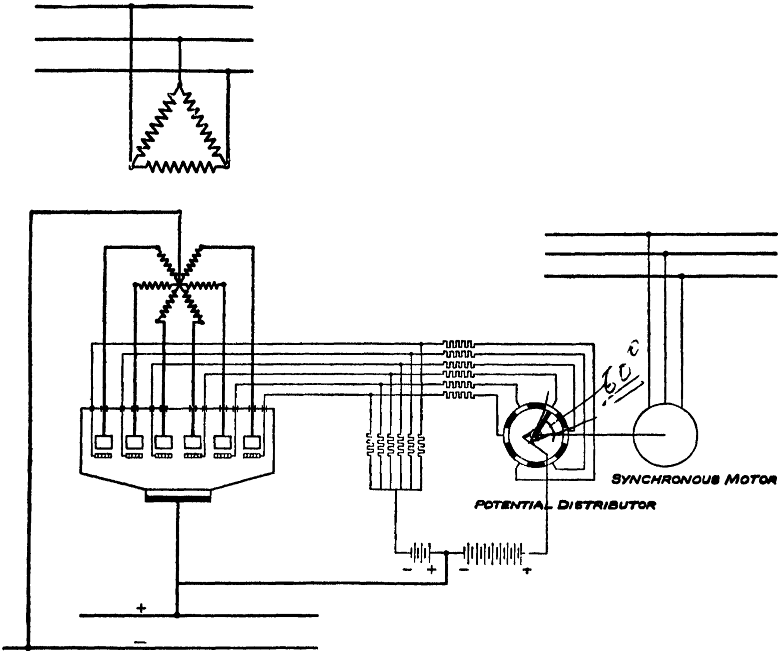


FIG. 80. DIRECT-CURRENT IMPULSE SYSTEM OF GRID CONTROL
English Electric Co.

angles to one another, and by strengthening or weakening one or other of these, the rotor can be advanced or retarded in phase, relative to the rotating field of the stator. By making the ampere-turns of the variable field winding dependent upon the load current of the rectifier any desired voltage characteristic can be obtained, the response between rectifier voltage and load current being instantaneous as in the case of a direct-current machine provided with a series winding.

The above direct-current impulse system of grid-control has been successfully applied to steel-tank rectifier units with the object of giving to them either a level-compound or an over-compound voltage characteristic.* In the case of glass-bulb rectifier equipment, where the amount of grid current flowing during the brief periods of positive potential impulse is much less, it is possible to make use of alternating-current systems of impulse control which have the advantage of being entirely static in operation. One such method of control employs a normal grid regulator of the type depicted in Fig. 71 to supply several potential transformers, which are so designed as to give a secondary voltage having a very peaked wave-form. The control grids are then each connected to one end of the several secondary windings, the other ends being joined together and to the cathode in the usual way. The requisite

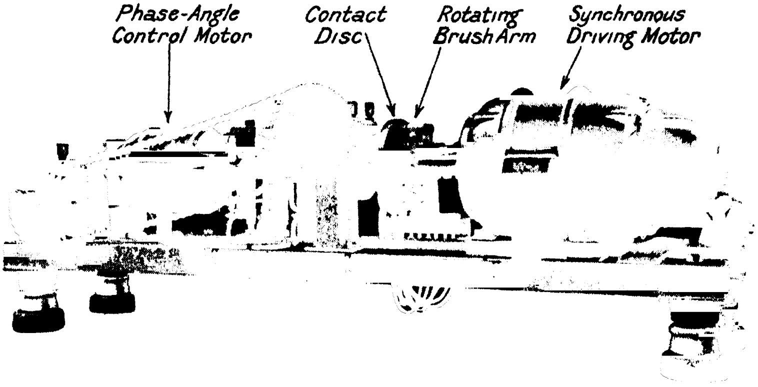


FIG 81 DIRECT-CURRENT IMPULSE TYPE OF GRID-CONTROL UNIT FOR AUTOMATIC VOLTAGE CONTROL

English Electric Co

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* *Cf.* Chapter XVI

phase displacement between the grid-voltage impulses and the corresponding anode voltages is then obtained by adjustment of the induction regulator supplying the "peaking" transformers. This system has the disadvantage, however, that when applied to automatic voltage control it is not instantaneous in operation; there remains always the inherent time-lag of the mechanism for operating the induction regulator.

An alternative system of impulse control in which this drawback is not apparent, is illustrated diagrammatically in Fig. 82. This particular system makes use of small highly-saturated grid-excitation transformers for providing the potential impulses. These special control transformers have magnetic circuits of high-permeability material, such as "Permalloy," and are each provided with three windings indicated as 1, 2 and 3 in the circuit diagram of Fig. 82. Of these three, two are exciting windings; windings 1 are connected in delta, whilst windings 2 are star-connected through a rheostat R_v. Each delta winding carries a sinusoidal magnetizing current i_k which is limited by the fixed series resistance R_k. The corresponding star windings carry a magnetizing current i_v which is displaced from i_k by 150 electrical degrees (the angle equal to $[\pi - \theta]$ in diagram

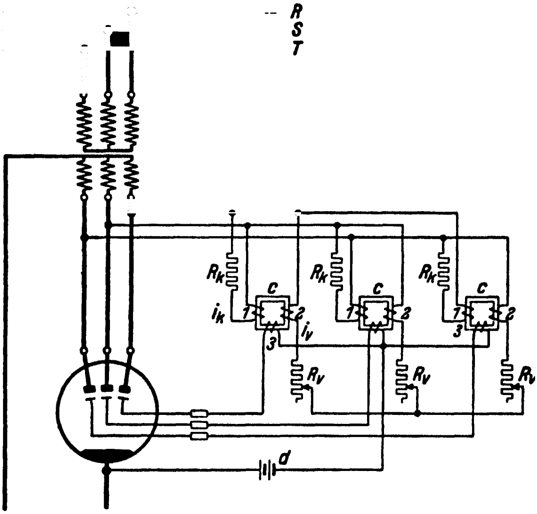

FIG. 82. ALTERNATING-CURRENT IMPULSE SYSTEM OF GRID-CONTROL
Siemens-Zeitschrift

(*b*) of Fig. 83) and whose amplitude is determined by the setting of the star-point rheostat R_v. The third winding 3 on each transformer is the potential-impulse winding supplying the control grid. These windings are star-connected and the common neutral point is connected to a source of negative biasing potential *d*, indicated as a small battery in Fig. 82. In practice the negative bias is generally provided by means of a suitably connected metal-oxide rectifier.

The mode of operation of this alternating-current impulse system of grid-control may be seen from the diagrams of

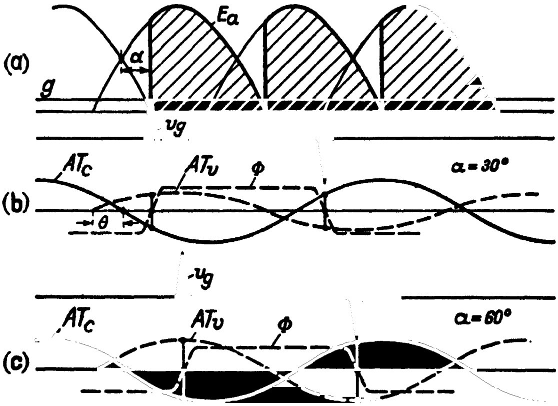

FIG. 83. OPERATION OF SATURATED-TRANSFORMER IMPULSE SYSTEM
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Fig. 83. Diagram (*a*) shows the potential of the grids in relation to the corresponding anode voltages. It consists of a constant negative blocking potential on which is superimposed a sharply-peaked alternating impulse voltage. The latter is obtained as follows: In diagram (*b*) the sine wave AT_c represents the ampere-turns of winding 1, whilst AT_v represents the corresponding ampere-turns of winding 2. At the instant in the alternating-current cycle in which these have equal and opposite values the flat-topped flux wave Φ suddenly changes sign, inducing a positive voltage impulse in winding 3, as shown by diagram (*a*), which relates to an ignition angle $\alpha = 30°$. A corresponding negative voltage impulse occurs 180° later, but this is of no consequence to the operation of the grid-control system.

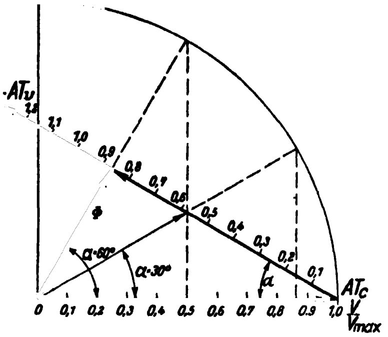

FIG. 84. VECTOR DIAGRAM FOR IMPULSE CONTROL SYSTEM OF FIGS. 82 AND 83

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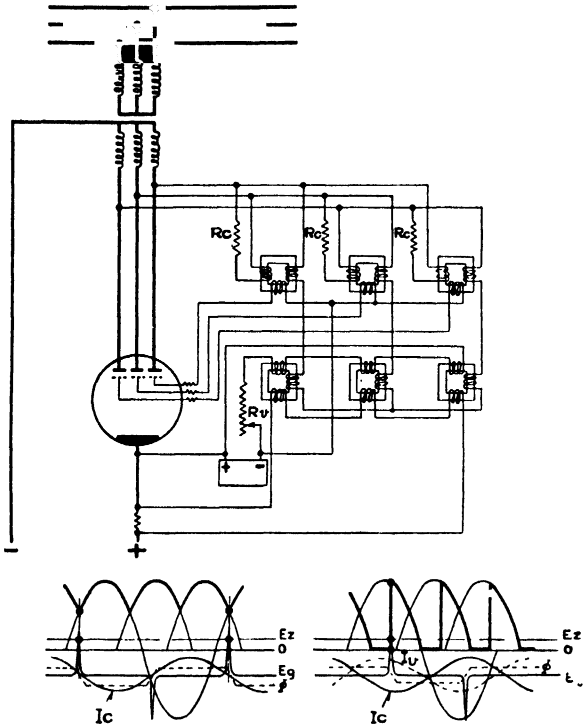

FIG. 85. AUTOMATIC VOLTAGE CONTROL WITH SATURATED-TRANSFORMER IMPULSE SYSTEM OF GRID CONTROL

R_c = Fixed excitation resistors
R_v = Premagnetizing circuit rheostat
E_z = Ignition potential
O = Cathode potential
E_g = Grid-excitation voltage
I_v = Variable exciting current
I_c = Constant exciting current
ϕ = Resultant magnetic flux

English Electric Co.

By altering the amplitude of i_v through adjustment of the rheostat R_v the ignition angle may be varied, as shown by diagram (c), for which $\alpha = 60°$. The relation between the rectifier voltage V (expressed as a fraction of the maximum value V_{max} occurring with fully-advanced arc ignition), the ignition angle α, the ampere-turns, and the resultant flux Φ in the magnetic circuit of the grid-excitation transformer, is shown by the vector diagram of Fig. 84.

Instead of the variable alternating-current excitation i_v, direct-current magnetization can be employed, and in this way the instant of arc ignition can be made dependent on the load current as in the case of the direct-current impulse system of grid control. Another circuit of this type used to obtain a compound voltage characteristic is illustrated by Fig. 85. Here the variable ampere-turns of each impulse transformer are determined by choke coils arranged on cores which are magnetically saturated by direct current obtained from two sources. One of these is the source of potential for providing the negative bias on the grids; the other is a divertor in the direct-current load circuit of the rectifier. The direct-current ampere-turns due to the former are constant, whilst those due to the compounding coils vary with the rectifier load. As the result, the impedance of the choke coils decreases with increasing load, and the variable ampere-turns of the impulse

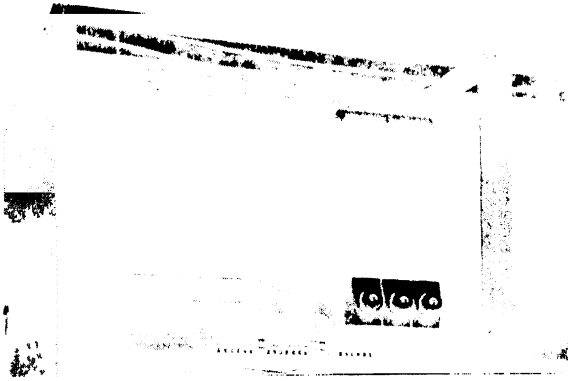

FIG. 86. SATURATED-TRANSFORMER TYPE OF AUTOMATIC GRID-CONTROL UNIT
English Electric Co.

transformers are reduced. The voltage impulses applied to the control grids are thereby advanced in phase, and the output voltage from the rectifier thus tends to rise. This arrangement of automatic voltage control is ideal for compounding traction rectifiers, as it is both instantaneous and entirely static in operation. Load sharing between any number of rectifiers connected in parallel is assured by the use of an equalizer connection, as in the case of a rotary convertor or direct-current machine. Fig. 86 illustrates an automatic grid-control equipment of this type as manufactured by the English Electric Co.*

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* See also Chapter XVI.

CHAPTER X

THE GRID-CONTROLLED MERCURY-ARC RECTIFIER

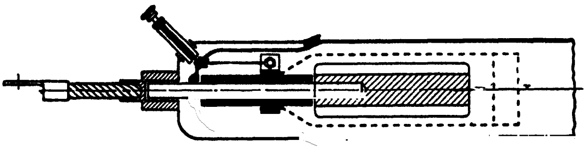
THE systematic investigation during the past decade of the physical behaviour of the mercury-arc rectifier under the most diverse operating conditions and, more particularly, the research work carried out to ascertain the nature and causes of the phenomenon known as back-firing, has not only led to the present perfection of this class of apparatus, but has contributed largely to the development of the *grid-controlled rectifier*. To-day, steel-tank as well as glass-bulb rectifiers are

FIG. 87. 400-A GLASS-BULB RECTIFIER WITH CONTROL GRID
English Electric Co.

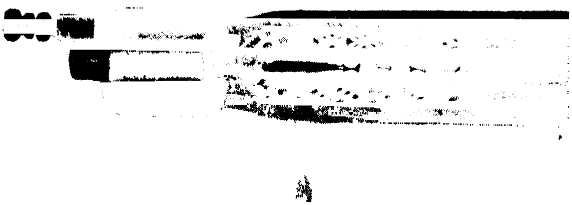
available for all outputs either equipped with control grids or not according to the type of service to which they are to be applied.

Speaking generally, the grid-controlled rectifier is distinguished from its prototype only in the arrangement of the anode sheaths and by the inclusion of control grids and their connections.

Fig. 87 illustrates a typical glass-bulb rectifier provided with control grids, from which it is seen that the general design follows that of the normal type of rectifier depicted in Fig. 31. Details of the anode and grid construction are given in Fig. 88. With this particular design the grid completely surrounds the anode and takes the form of a perforated metal basket. In the design of control grid adopted in connection with rectifiers of the type illustrated in Fig. 34, the grid is placed some distance in front of the anode and consists of a short metal cylinder, to the inner circumference of which are attached radial fins (Fig. 89).



(*a*) Diagrammatic cross-section
Siemens-Schuckert Werke



(*b*) General view
English Electric Co.

FIG. 88. BASKET TYPE OF CONTROL GRID

In the case of rectifiers of the steel-tank type, the design and arrangement of the control grids also present no unusual features. Fig. 90 shows a section through a typical grid-controlled rectifier as manufactured by the English Electric Co. This particular unit has a rating of 2 500 A at pressures up to 800 volts, direct current. The method by which the insulated connection to the grid is brought out through the anode plate is similar to that employed in the case of the main anode connections. A 500-kW 500-volt grid-controlled unit of the steel-tank type as constructed by the General Electric Co. is illustrated in Fig. 91.

Circuit Interruption by Grid Excitation. An extremely valuable characteristic of the grid-controlled rectifier is that by which the apparatus is rendered self-protecting. By the use of grid control the rectifier can be made to act as its own circuit-breaker, so that in the event of a short-circuit or a back-fire the current arc is interrupted without mechanical interruption of either the alternating-current supply or the direct-current circuit.

If a negative potential is suddenly applied to all the grids, the normal commutation of the arc from anode to anode is interrupted and the arc cannot re-establish itself. In effect, the rectifier becomes its own circuit-breaker. Oil switches of large rupturing capacity on the alternating-current side and high-speed circuit-breakers on the direct-current side are thus no longer essential to the protection of rectifier equipment. This important feature of grid control has been successfully applied to rectifiers for supplying high-tension direct current to broadcast transmitters as well as to heavy-duty rectifiers for traction service, and is tending to become standard practice for the protection of the larger rectifier installations.

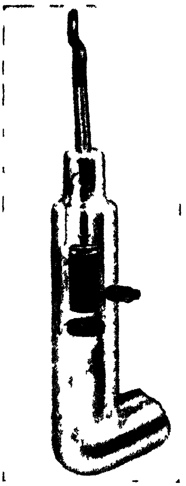


FIG. 89. PLATE SHIELD TYPE OF CONTROL GRID

Bruce-Peebles & Co.

Two alternative methods of grid control are available for effecting interruption of the power circuit. In the first alternative the grids are not energized at all during normal operation of the rectifier, that is, they remain neutral and take up a potential equal to the arc which envelops them; but immediately upon the occurrence of a fault they are given a negative or *blocking* potential. In the second alternative, under normal conditions, grid excitation is arranged so that the arc is ignited at each anode in turn by the application of appropriate positive impulses to the grid, which, being *liberating* potentials, momentarily wipe out the effect of a permanent negative grid-bias: when, however, a short-circuit occurs the positive potentials are no longer permitted to reach the grids.

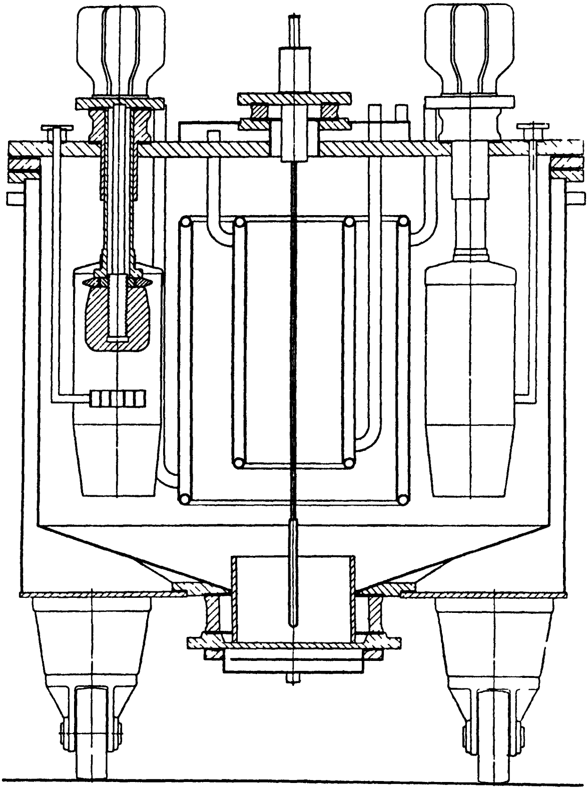


FIG. 90. 2 500-A. GRID-CONTROLLED STEEL-TANK RECTIFIER
English Electric Co.

The former method of circuit interruption—which may be termed the *closed-circuit* system—is illustrated diagrammatically in Fig. 92. A special type of high-speed relay, operating in less than 1 millisecond, is energized by a current transformer in the alternating-current circuit (or from a suitable ammeter-shunt type of divertor in the load circuit). In the event of a sudden overload or a back-fire the relay closes and applies a blocking potential to the grids. The particular anode which is carrying the current arc at the instant the relay operates will continue to function until its voltage passes through zero at the end of the corresponding positive half-cycle, but the next

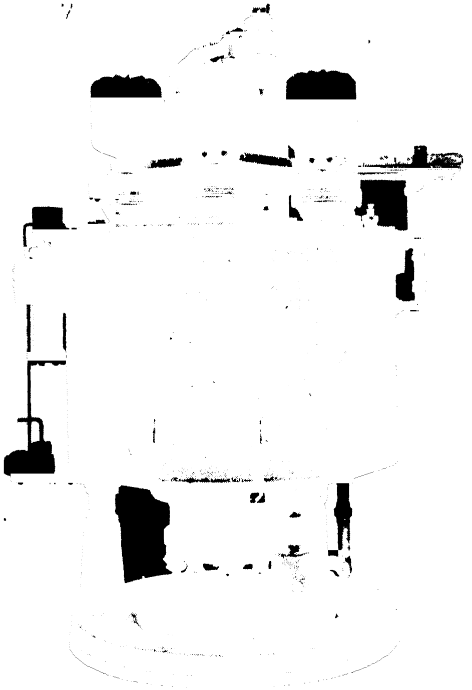


FIG. 91. 1 000-A. GRID-CONTROLLED STEEL-TANK RECTIFIER
General Electric Co.

anode in the commutation sequence is prevented from picking up the arc by reason of the fact that its grid has in the meantime been given a strong negative potential. In this connection it is important to note the maximum duration of time between the closing of the relay contacts and the extinction of the arc. In the extreme case, where the relay operates at the earliest possible instant in the anode voltage-cycle, the time elapsing before the arc is finally extinguished is seen to be 6·5 milliseconds for a six-phase rectifier, and 10 milliseconds

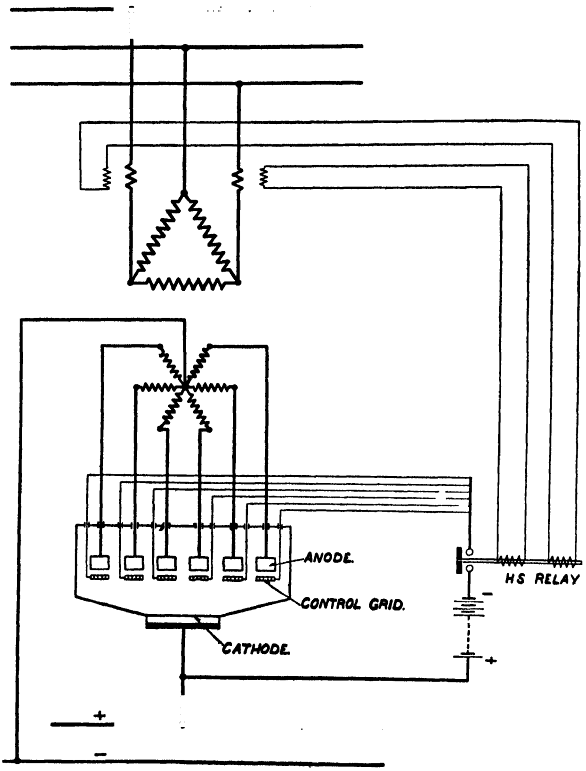


FIG. 92. CLOSED-CIRCUIT SYSTEM OF LOAD SWITCHING BY GRID CONTROL

English Electric Co.

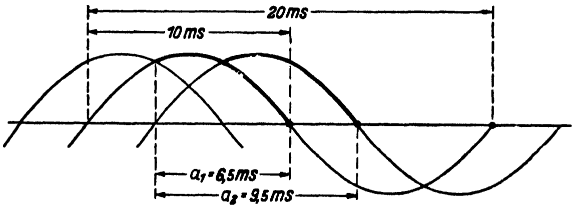


FIG. 93. DIAGRAM SHOWING MAXIMUM ARCING TIMES IN SIX-PHASE 50-CYCLE RECTIFIERS EMPLOYING GRID CONTROL FOR LOAD SWITCHING

Siemens-Zeitschrift

for a double three-phase rectifier, as indicated by a_1 and a_2 in Fig. 93.

The other method of circuit interruption—which may be termed the *open-circuit* system—is shown in Fig. 94, and is especially applicable to impulse systems of grid-excitation as described in the previous chapter. In this case the illustration refers to a direct-current impulse system such as that of Fig. 80.

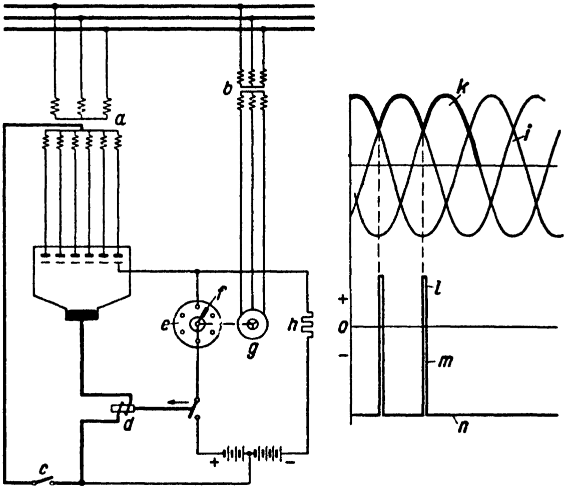


Fig. 94. Open-circuit System of Load Switching by Grid Control

a = Rectifier transformer
b = Auxiliary transformer
c = Short-circuiting switch
d = High-speed relay
e = Impulse distributor
f = Rotating brush
g = Synchronous motor
h = Current-limiting resistor
i = Anode voltage
k = Direct current
l = Liberating potential
m = Instant of short circuit
n = Blocking potential
o = Cathode potential

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It is seen that with this system of load switching the relay contacts are opened in the event of a fault occurring on the direct-current side, thereby interrupting the supply of positive potential impulse to the several control grids. Both systems lend themselves readily to remote control of the opening or closing of the power circuit.

However powerful the arc, the circuit will be interrupted quite naturally, and the entire absence of heavy mechanical parts ensures a considerable reduction in the time taken to clear a fault or a back-fire. The oscillograph record of Fig. 95

shows the interruption of a dead short-circuit in the case of a heavy-duty traction rectifier rated to carry a full-load current of 2 500 A at 800 volts. It is seen that approximately 15 milliseconds elapsed between the incidence of the fault and the operation of the relay, this being the time required for the flux to build up in the current transformer as well as in the relay itself. By this time the current had risen to 10 times its initial value. The extreme rapidity with which the short-circuit current arc was extinguished is clearly demonstrated in this oscillogram, the actual time taken being only 5 milliseconds.

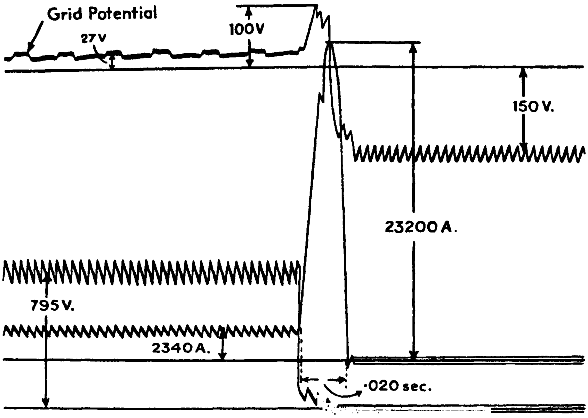

FIG. 95. OSCILLOGRAM SHOWING CIRCUIT INTERRUPTION BY GRID CONTROL
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Where necessary, the high-speed relay can be arranged to reclose very quickly, so that if the short-circuit is only momentary the supply from the rectifier is not permanently interrupted. On the other hand, should the fault persist the rectifier will be locked out. A reclosing arrangement of this type operating in about one-fifth of a second, and applied to some of the heavy-duty rectifiers supplying the Berlin City Circular and Suburban Railway, is shown in Fig. 96. On the occurrence of a short-circuit the high-speed relay operates and locks itself in by the catch g_2; in doing so it pushes over the mercury switch towards the left-hand position. When this switch is half-way in its travel it momentarily closes the contacts u, v, thereby energizing the solenoid g_1 and releasing the catch g_2.

The high-speed relay is thus pulled back into its initial position under the influence of a spring, the contacts *h* are opened, and the power circuit is consequently reclosed. In the meantime, however, the mercury switch has reached its left-hand position, in which the contacts *u*, *v* remain permanently open. Should the short-circuit recur, the high-speed relay will operate again, but will remain locked in position by the catch g_2. The latter cannot be released, and the relay re-set, until the push-button *e* is operated by the substation attendant.

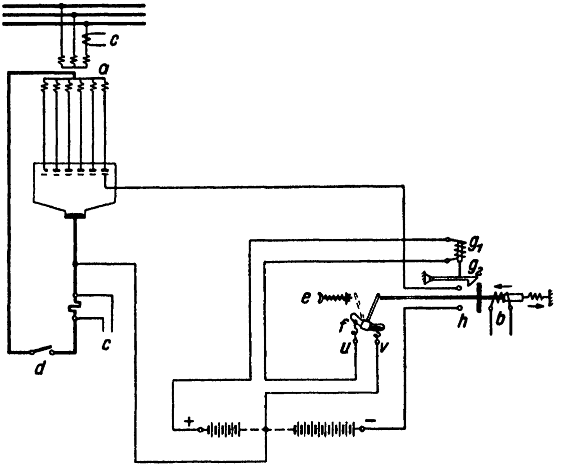

FIG. 96. AUTOMATIC RECLOSING OF HIGH-SPEED RELAY IN GRID-EXCITATION CIRCUIT

a – Rectifier transformer
b = High-speed relay coil
c = Alternative connections to H.S. relay coil
d – Short-circuiting switch coil
e – Resetting push-button
f = Mercury switch
g_1 – Reclosing solenoid
g_2 = Reclosing release
h · H.S. relay contacts
v, *v* – Mercury switch contacts

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Voltage Variation and Compounding by Grid Control. In many cases, particularly where rectifiers are installed in power and lighting substations, the demand arises for regulation of the output voltage from the rectifier. Until the advent of the grid-controlled rectifier this requirement could only be met by altering the voltage applied to the rectifier on the alternating-current side either by means of on-load tap-changing on the rectifier transformer or by the provision of an additional boosting transformer or induction regulator. A more efficient and less costly method of regulating the output voltage, however, is that employing grid-control of the rectifier itself.

As was explained in the preceding chapter, this method is based on the fundamental consideration that the average value of the rectified voltage (V in Fig. 78) depends on the phase of the arc commutation in the anode voltage-cycle. The later the phase position (i.e. the greater the ignition angle α in Fig. 78) the lower is the output voltage from the rectifier. The relation between the two may be determined as follows—

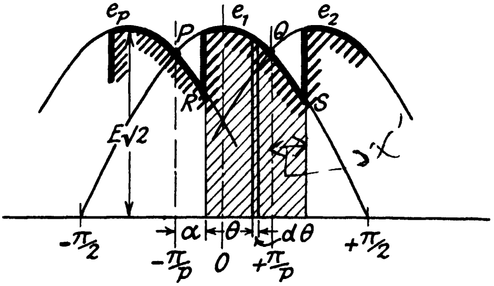

FIG. 97. VOLTAGE VARIATION BY GRID CONTROL

If, as shown in Fig. 97, the instant of arc ignition is delayed by the angle α then the anode whose voltage is indicated by the curve e_1 will carry current over a period represented by the time interval between R and S, instead of over the normal period corresponding to the time interval between P and Q. The ignition angle α is the angular displacement between P and R, or Q and S. Consequently the voltage at the rectifier terminals is equal to the mean value of e_1 over the period $R - S$, that is, of the area under the curve shown shaded in Fig. 97. The anode voltages are each expressed by the general equation $e = E(\sqrt{2}) \cdot \cos\theta$, in which $-\pi/p < \theta < +\pi/p$. Hence we have for the direct-current output voltage

$$V_d = p/2\pi \cdot E\sqrt{2}\int_{\alpha-\pi/p}^{\alpha+\pi/p} \cos\theta \cdot d\theta = \frac{pE\sqrt{2}}{2\pi} \cdot \Big[\sin\theta\Big]_{\theta=(\alpha-\pi/p)}^{\theta=(\alpha+\pi/p)}$$

$$= \frac{pE\sqrt{2}}{2\pi} \cdot 2\cos\alpha\sin\pi/p$$

$$= \frac{(\sqrt{2}) \cdot E \cdot p}{\pi} \sin\frac{\pi}{p} \cdot \cos\alpha = V_{d_0} \cdot \cos\alpha. \qquad (25)$$

where V_{d_0} is the maximum possible value of V_d, corresponding to $\alpha = 0$, i.e. to the case of a rectifier operating normally. The above result is of considerable importance, and may be stated in the following form: *In the case of a rectifier operating at reduced voltage by grid control, the ratio of the actual output voltage to the normal (maximum) output voltage, as determined by the number of rectifier phases, is equal to the cosine of the angle by which the instant of arc commutation is retarded from its normal phase position in the anode voltage-cycle.*

The significance of this result is at once realized by a comparison between Figs. 97 and 9, and between the corresponding equations (25) and (1). With $\alpha = \pi/2$, $\cos \alpha$ becomes zero, and no voltage appears at the direct-current terminals of the rectifier. When $\alpha = \pi$, we have $\cos \alpha = -1$; so that $V_d = -V_{d_0}$. This condition corresponds to inverted or regenerative operation of the rectifier, and will be dealt with more fully in the next chapter. It can only arise in practice if there exists an appropriate "driving" e.m.f. in the direct-current circuit and, at the same time, a corresponding back e.m.f. in the windings of the rectifier transformer. Another important feature of grid control as applied to voltage variation is also apparent from Fig. 97. It is seen that the *axis of current conduction* for any particular anode is no longer coincident with the point of maximum anode voltage. In other words, anode voltage e_1, for example, which is effective between $\theta = -\pi/p$ and $\theta = +\pi/p$, produces an anode current which flows not during the same interval (as in Fig. 9), but during the interval from $\theta = (\alpha - \pi/p)$ to $\theta = (\alpha + \pi/p)$. These two intervals are of the same duration, but the latter lags the former by the phase angle α. *In a grid-controlled rectifier, therefore, the anode currents lag behind their corresponding anode voltages by the same angle* α *by which the instant of arc commutation is delayed.*

The above consideration is evident if it is remembered that in a normal rectifier the "centre of gravity" of the anode-current wave lags behind that of the anode-voltage wave by a certain angle* which is a function of the angle of overlap u. And just as much as the effect of transformer reactance is to give rise to this phase displacement, and to an accompanying drop in the output voltage from the rectifier, so in the case of grid control the existence of an angle of phase displacement —the ignition angle α—is accompanied by a similar drop in output voltage. In the former case the relation is expressed by $V_d = V_{d_0} . \cos^2 (u/2)$; whilst, in the latter case, it is given by $V_d = V_{d_0} . \cos \alpha$. In both cases the effect of this phase displacement on the alternating-current side of the rectifier appears as a reduction in the power factor. This question will be treated in detail in a subsequent chapter.

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* *Vide* Chapter XIV.

By virtue of its control grids, then, the mercury-arc rectifier provides a simple and reliable means of controlling the speed of large direct-current motors; for example, by direct regulation of the armature voltage. In a similar way grid control can give to rectifiers for either traction or lighting duty a level-compound, or an over-compound voltage characteristic. This important feature was discussed in the preceding chapter, which also dealt with systems of compounding rectifiers that have been successfully employed in practice. The fact that the relation between the output voltage V_d and the ignition angle α is not linear, but varies according to a cosine law, is of little practical importance. It is possible, however, to devise systems of rectifier compounding in which a relation between the load current and the ignition angle is obtained which results in a linear voltage response.

Rectifier Excitation of Synchronous Machines. Up to the present, synchronous alternating-current machines have been either of the separately-excited or of the self-excited type, that is to say, a special source of direct-current has always had to be provided in order to supply the necessary excitation. In the former type of synchronous machine use is made of some extraneous direct-current supply; whilst in the case of the latter type the excitation supply is derived from an exciter directly coupled to the shaft of the machine. It is not generally realized that such an alternator or motor can be excited without having recourse to either of these methods of direct-current supply. An analogy will make this clear.

Take, for example, the simple case of a shunt-wound direct-current machine. Here the alternating current which is originally generated in the armature winding is changed into direct current by means of the commutator, and this direct current is utilized to excite the field of the machine. Now in the case of a synchronous alternating-current machine the exciting voltage can be taken in the same way directly from the machine terminals, but in this case the commutator is most conveniently replaced by some form of static rectifier. By far the most important means of rectifying the alternating voltage delivered at the terminals of the synchronous machine so as to obtain the necessary direct-current excitation supply consists in employing a mercury-arc rectifier provided with grid control, because the grid-control feature can be utilized to obtain an automatic regulation of the machine voltage. For example, the excitation can be made dependent upon the load current, or upon the power factor of the machine. Moreover it is possible to arrange the grid-control gear so as to give a rapid voltage response in the case of disturbances in the alternating-current system to which the machine is connected.

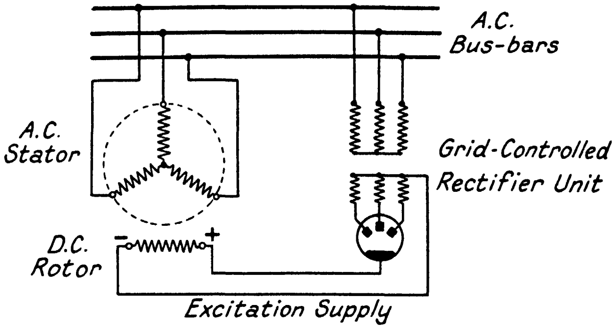

Fig. 98. Rectifier-excited Synchronous Alternating-current Machine

The fundamental circuit of such a rectifier-excited alternating-current machine is given in Fig. 98. The rotor winding receives its excitation supply from a grid-controlled rectifier unit connected on the alternating-current side to the machine terminals or the e.h.t. busbars. The field excitation can be varied by altering the setting of the grid-control gear associated with the rectifier unit (not shown in the diagram), and in this way the terminal voltage of the machine, or the power factor, may be altered as desired. The variation of machine voltage with field excitation—expressed in terms of the output voltage of the rectifier unit—for different values of the ignition angle α is shown in Fig. 99, which relates to a small 50-cycle alternating-current generator excited from a three-phase rectifier unit. The resistance of the field winding was 34 ohms, whilst its inductance amounted to 20 henries, giving a reactance of 6 283 ohms. The load on the excitation rectifier in a combination of this kind is thus almost entirely inductive, with the result that the alternating-current component of the exciting current—due to the harmonic ripple in the output voltage from the rectifier unit—is negligible, even with large values of α. In this particular case with a reduced rectifier voltage corresponding to $\alpha = 90°$, the total r.m.s. harmonic ripple in the excitation current supplied to the field winding did not exceed 0·5 per cent of the mean value.

By converting the excitation voltage values of Fig. 99 to

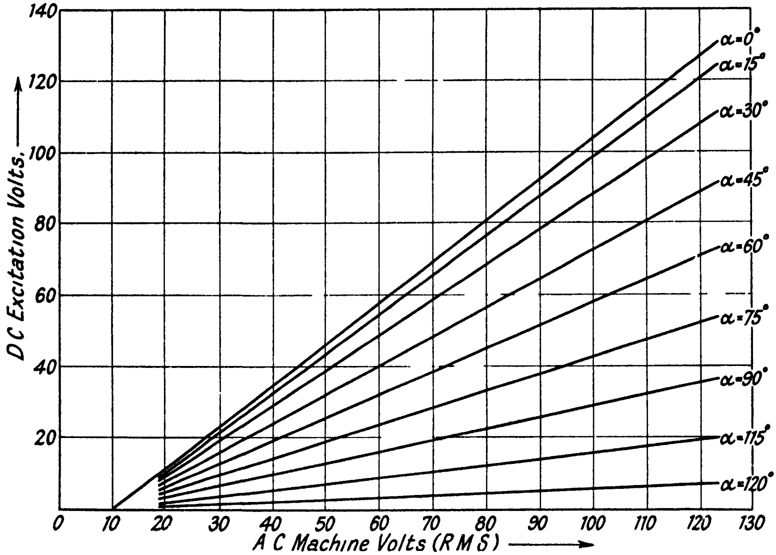

FIG 99. RECTIFIER EXCITATION CHARACTERISTICS

amperes a fresh set of rectifier excitation characteristics for the machine may be drawn up, as shown in Fig. 100. The open-circuit characteristic is also indicated on the diagram. It is seen, in the first place, that all the rectifier characteristics emanate from a point O corresponding to a definite machine voltage E_0 at zero excitation. The value of E_0 is the alternating-current equivalent of the arc drop ε_a in the excitation rectifier. At the same time the open-circuit characteristic also commences at a definite voltage E_r which is that generated by the remnant magnetism of the machine. Secondly, it is seen that certain of the rectifier characteristics intersect the open-circuit characteristic, and at points corresponding to different machine-voltage values; whilst others do not give any point of intersection.

Considering the rectifier characteristic corresponding to $\alpha = 90$, for example, it is seen that it is intersected at two points, P and P', by the open-circuit characteristic. The upper point (P) denotes a state of stable excitation, when a tendency for the excitation current, i.e. the field strength of the machine, to increase is no longer maintained by a corresponding augmentation of the output voltage from the excitation rectifier unit. In other words, at this point the cumulative building-up of the machine voltage ceases. In the case of the lower point (P') of intersection the machine excitation is unstable. On the one hand the voltage of the machine may build up gradually until it reaches a value corresponding to the point P; whilst, on the other hand, it may equally well fall away rapidly to the value E_r corresponding to zero excitation. A diagram such as that of Fig. 100 thus provides a general indication as to the behaviour of an alternating-current machine excited

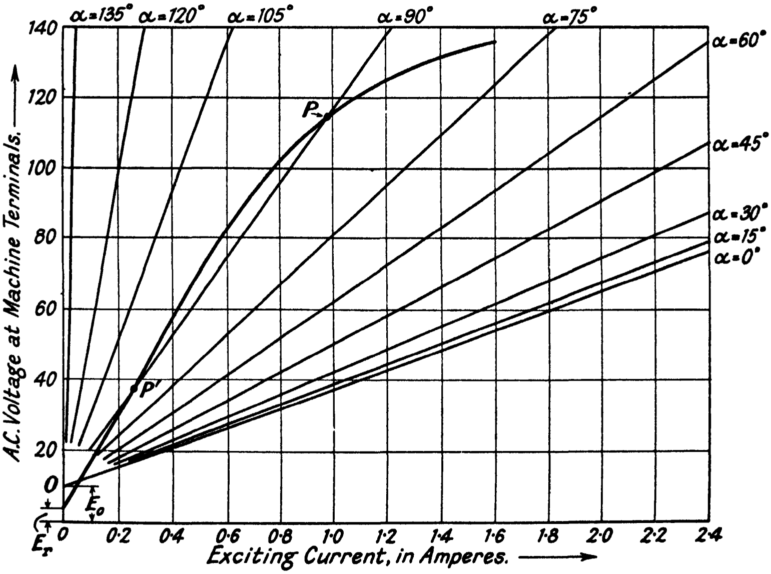

FIG. 100. SELF-EXCITATION CHARACTERISTICS OF ALTERNATING-CURRENT GENERATOR

from a rectifier supplied from the machine itself. In particular, it is evident that the machine will not be self-exciting if $E_o > E_r$, which will occur, in general, only in the case of small machines such as that considered above. The stability of the point P depends, like the correcting time, upon the angle at which the open-circuit characteristic intersects the rectifier characteristic. The larger this angle, the greater will be the degree of stability and the shorter will be the time taken to correct voltage variations. In view of these factors, the design of alternating-current machines arranged for self-excitation by means of rectifier equipment will be influenced by the further consideration as to whether the regulation of the machine is to be "coarse" or "fine."

The Direct-current Rectifier Locomotive. The application of the principles of grid-control to rectifier practice has given a fresh impetus to the development of the *convertor locomotive* as a possible form of electric tractor. This type of electrically-propelled locomotive is essentially one in which the supply current and motor current are not only different as regards voltage, but are also of dissimilar form; and in such locomotives the necessary means of current conversion have hitherto been limited to rotating machines of a complicated, expensive, and relatively inefficient nature. One of the best-known examples of the convertor locomotive is that developed by the late Kálman Kandó for the Hungarian State Railways.*

The advent of the steel-tank rectifier, however, opened up fresh possibilities in that the heavy rotating convertor, which is the distinctive feature of the convertor locomotive in all its forms, could for the first time be replaced by a static piece of apparatus at once lighter and more efficient. The first complete design of such a *rectifier locomotive* was put forward by Reichel towards the end of 1924,† and embodied a steel-tank rectifier unit with on-load tap-changing transformer for converting the three-phase alternating current, supplied to the overhead contact wires, to direct current at variable voltage for the traction motors. As this design did not offer sufficient advantages over the alternating-current locomotives then in

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* L. von Verebely: *Transactions of the First World Power Conference* (1924), Vol. IV, p. 983; *cf.* also *Elektrotechnisches Zeitschrift*, 1925, Vol. 46, p. 37; and *Elektrotechnik und Maschinenbau*, 1925, Vol. 43, p. 114.

† W. Reichel: *Zeitschrift des Vereines Deutscher Ingenieure*, 1925, Vol. 69, p. 52.

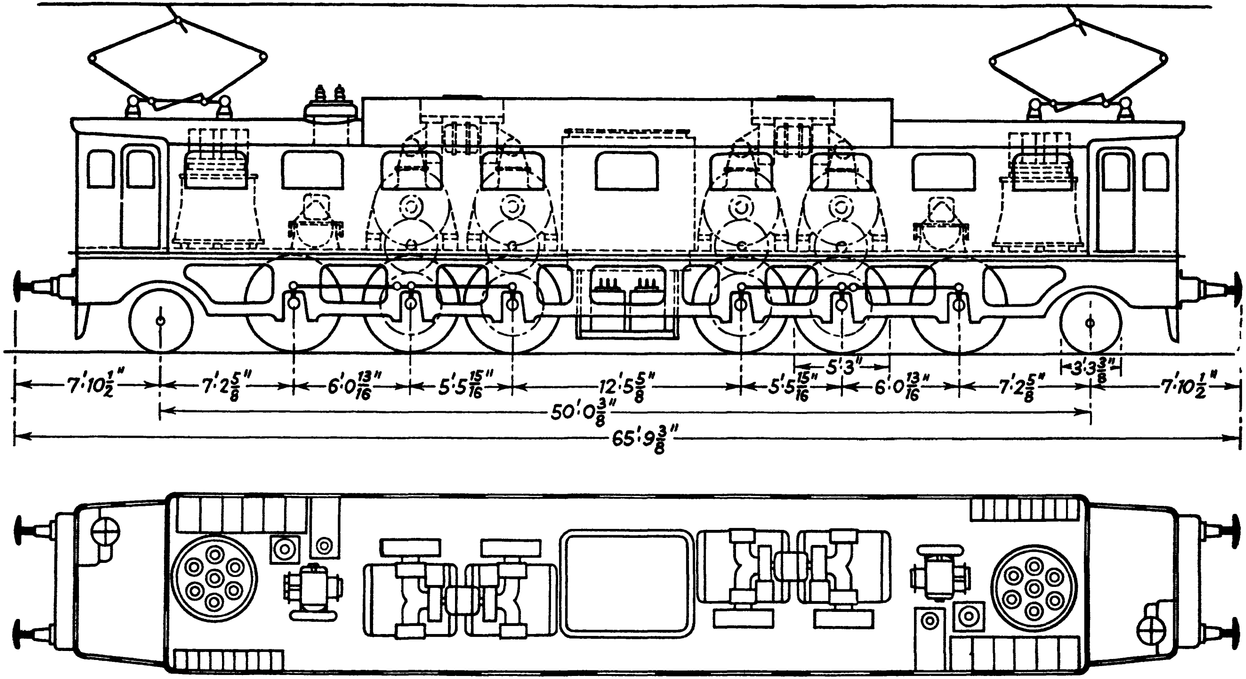

FIG. 101. DIRECT-CURRENT RECTIFIER LOCOMOTIVE

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use on the German State Railways system for it to become of real practical importance, Reichel revised his design in the light of further advance in rectifier technique, including the application of grid-control, and modified it so as to accord with the system of single-phase alternating-current supply which in the meantime had become almost standard practice.* Fig. 101 illustrates this revised design as applied to a high-speed passenger locomotive of the type built in considerable numbers for the German State Railways in 1924. Here, for the first time, the fundamental advantage of the rectifier locomotive—its complete independence of frequency—was realized to the full; moreover, compared with the usual alternating-current locomotives of the same output, and operating from a single-phase supply at 16⅔ cycles per second, the 50-cycle rectifier locomotive showed a saving in weight of no less than 15 per cent. In addition, the introduction of the rectifier locomotive now permits the traction system to be coupled directly to and, in fact, to be supplied from, industrial and other electricity supply networks. Furthermore, the inclusion of the grid-control feature allows the traction motors to be controlled without appreciable energy loss, and with a degree of smoothness unattainable by any other electrical means.

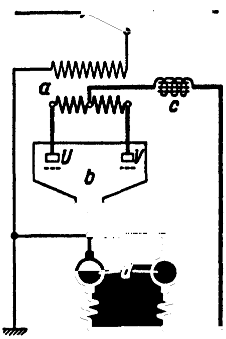

FIG. 102. FUNDAMENTAL CIRCUIT DIAGRAM OF THE DIRECT-CURRENT RECTIFIER LOCOMOTIVE

a = Single-phase transformer
b = Grid-controlled rectifier
c = Smoothing reactor
d = Traction motors
u, *v* = Rectifier anodes

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The schematic diagram of the single-phase rectifier locomotive, incorporating direct-current traction motors of the usual series type, is given in Fig. 102 in its simplest form. Speed control of the motors is then obtained by varying the motor voltage, through the medium of suitable grid-control gear. The rectified voltage obtained with this arrangement is shown in diagrams (*a*) and (*b*) of Fig. 103, the former relating to "full voltage," and the latter to "half voltage" applied to the motors. In these diagrams E_u and E_v are the voltages of anodes *U* and *V* with respect to the transformer neutral. The effective voltages applied to the direct-current load circuit are indicated by the shaded areas. Due to the presence of the smoothing reactor the direct current flows uninterruptedly in the load circuit, even when—as in diagram (*b*)—the driving e.m.f. momentarily disappears. Thus when the current arc is established at anode *U* at the instant corresponding to the point *A* in the diagram, it is not extinguished when the anode voltage reaches zero at *B*, but current continues to flow until the instant in the anode-voltage cycle, corresponding to the point *C*, when the arc commutates to anode *V*. In effect, a back e.m.f. is present in the load circuit from *B* to *C*—shown by the horizontally shaded areas—which has to be overcome by the release of energy previously stored up in the smoothing reactor.

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* W. Reichel: *Elektrotechnisches Zeitschrift*, 1932, Vol. 53, p. 778.

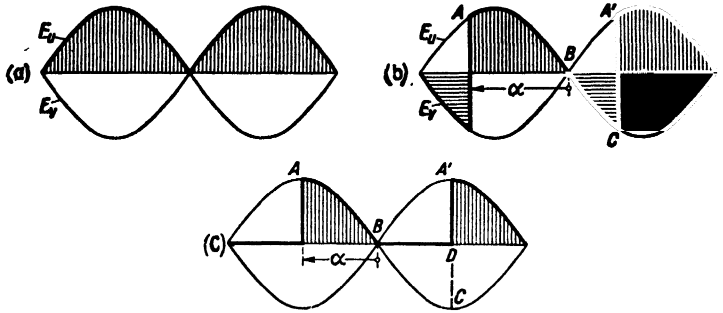

FIG. 103. VOLTAGE CONDITIONS

(*a*) At full motor voltage (*b*) At half voltage
(*c*) As in (*b*) but with neutral-point anode

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As the result, the direction of power flow reverses at *B* and only resumes its normal course again at *C*. In other words, the power flowing in the load circuit is oscillating. This characteristic phenomenon is accompanied on the one hand by a considerable reactive power consumption on the alternating-current side; and, on the other hand, by the necessity for the storage of a large amount of energy in the smoothing reactor on the direct-current side. These two conditions become worse the greater the reduction in motor voltage arising from a retarding of the instant of arc ignition, i.e. the greater the ignition angle.

Both disadvantages can be overcome by the provision of an additional anode connected to the neutral point of the transformer secondary and having no control grid—the so-called *neutral-point* anode; and, further, by duplicating the rectifier anodes proper and connecting the groups to points of the secondary winding having different voltages. The first arrangement is shown by diagram (*b*), and the second by diagram (*c*) of Fig. 104; whilst diagram (*d*) illustrates the combination of both which is employed in practice to obtain the desired improvement in power factor over the lower part of the voltage range.

The effect of introducing the neutral-point anode is shown by diagram (*c*) of Fig. 103, relating, like diagram (*b*), to half motor voltage. As before, anode U in Figs. 102 and 104 (*b*) carries current over the period from A to B. At B, however, the anode voltage becomes negative with respect to the potential of the transformer neutral—axis of abscissae in Fig. 103—so that the current arc then commutates naturally to the neutral-point anode O, which continues to carry the load current until point D is reached. At this point anode V is forced to pick up the current arc due to the action of the grid-control gear. As the result of this *modus operandi*, anode U is relieved of the necessity of carrying current whilst its voltage is negative (between B and C) and hence no energy reversal takes place during this period. The smoothing reactor is thus no longer required to store and release the energy equivalent of the area BCD, and consequently it need only be designed for its normal function of reducing the harmonics in the voltage and current supplied to the traction motors. A glance at diagrams (*b*) and (*c*) of Fig. 103 shows that the phase position of the point A, expressed for convenience by the angular displacement a of the grid-control gear from the zero-volts (standstill) position, is altered by the introduction of the neutral-point anode. In view of this fact, the grid-control characteristics, i.e. the relation between a and the motor voltage V, for the two cases will be different. This is clearly shown by the middle column of diagrams in Fig. 104. The right-hand column of diagrams shows the relation between the motor voltage V, the kW and kVAR inputs P and P_R, and the power factor cos ϕ on the primary side of the rectifier transformer.

The effect of subdividing the rectifier anodes into two groups connected to different voltage-sections of the transformer secondary is shown in diagrams (*c*) and (*d*) of Fig. 104. The grid-control of the two anode groups U_1, V_1 and U_2, V_2 is so arranged that, to start the motors, the motor voltage is first of all raised from zero to half volts—as in diagram (*d*)—by operation of the lower-voltage group. During this period the grid-control gear functions so as to render the higher-voltage anode group inoperative. At the end of this control period, corresponding to $\alpha = 120°$ in Fig. 104 (*d*)

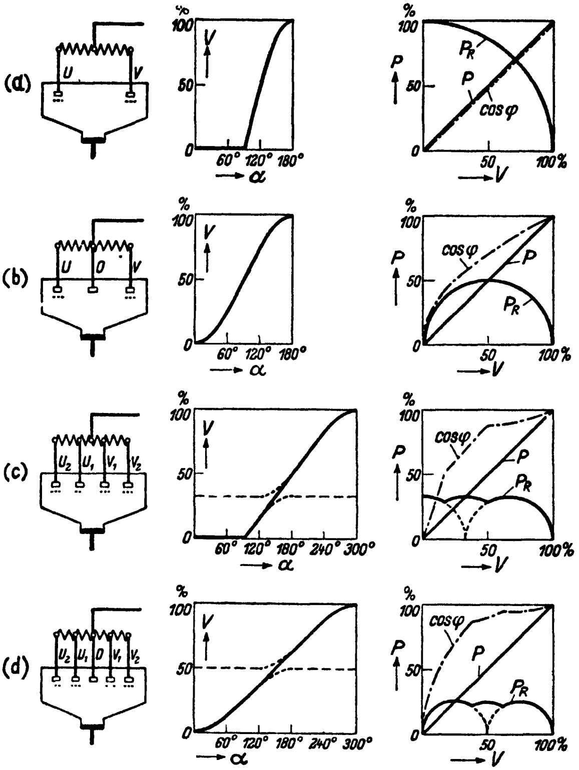

FIG. 104. DEVELOPMENT OF THE MULTIPLE-VOLTAGE ANODE CONNECTION

V = Percentage of maximum motor voltage
P = Percentage scale for P_R, P and cos ϕ

P = Kilowatts input
P_R = Reactive kVA input
cos ϕ = Power factor on A.C. side
α = Grid-control gear setting

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and Fig. 105, the higher-voltage group of anodes is brought into operation, and the instant of arc ignition at these anodes is gradually advanced until the motors are running at full speed under the maximum applied voltage. Fig. 105 illustrates clearly the manner in which the rectified voltage is gradually raised as the angular displacement ψ of the grid-control gear is increased. The simplicity of this new method of traction motor-control is evident from these diagrams. In particular it is to be noted that no mechanical interruption of the load circuit takes place during periods of voltage-control, a feature which is of paramount importance.

The curves of Fig. 106 relate to a practical example of a direct-current rectifier locomotive designed to operate from a single-phase supply at 6 600 volts and 25 cycles, and equipped with four 250 h.p., 575-volt, series-type motors permanently connected in series-parallel. The power-factor improvement obtained by multiple-voltage anode connection in conjunction with a neutral-point anode, as compared with the normal full-wave connection with simple grid-control of the output voltage, is clearly shown by the difference between the full-line and dotted power-factor curves.

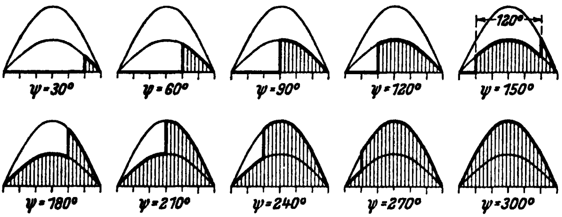

FIG. 105. VOLTAGE CONDITIONS WITH MULTIPLE-VOLTAGE ANODE CONNECTION

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It seems hardly necessary to point out that the application of the grid-controlled rectifier to the electric locomotive may in the near future revolutionize direct-current traction. Suffice it to state here that it presents the welcome advantages of simplicity and efficiency in operation, as well as a distinct saving in weight and capital cost.

The Alternating-current Rectifier Locomotive. It is in many ways unfortunate that no uniformity exists in the supply of electrical energy to railway traction systems. In some countries direct current at a pressure of 1 500, 3 000 or even 4 000 volts is favoured. But with such low voltages the number of points at which the overhead conductor has to be fed from the traction supply network is necessarily large, i.e. the distance between substations is not very great, and also the conductor cross-section is comparatively large. On the other hand, the direct-current traction motor is at once cheap and efficient, whilst its general robustness and reliability have rendered it unrivalled where the exacting demands of inter-urban and suburban traffic conditions have at all times to be met. But for main-line service with its heavy haulages of passenger and freight trains, its high speeds, and, not infrequently, its severe gradients, the economic advantages of a much increased supply voltage have in many countries led to the adoption of alternating-current traction systems, where

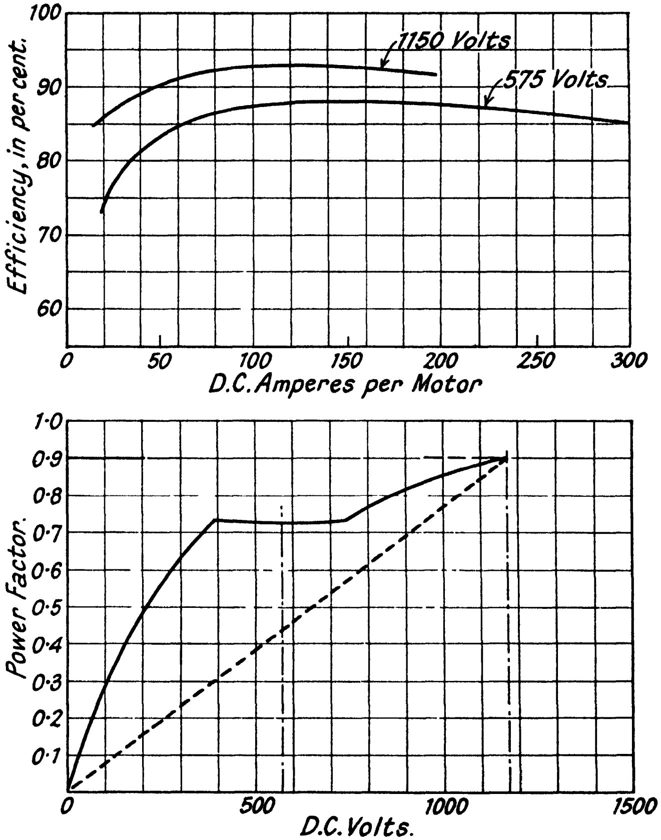

Fig. 106. Operating Characteristics of a 1 000-h.p., 1 150-volt Direct-current Rectifier Locomotive

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the pressure at the pantograph collector may be as high as 10 000 or 15 000 volts.

From the point of view of energy supply, the three-phase system would at first seem the most natural to adopt, as full use could then be made of existing power networks operating at industrial frequencies. But the many operating difficulties associated with such a system, e.g. the arrangement of triple overhead conductors at junctions, sidings and crossings, have resulted in its abandonment in favour of a system of single-phase supply at much lower frequencies—generally, 15, $16\frac{2}{3}$ or 25 cycles per second. In this case the practical necessity of a single overhead conductor carries with it the need for a reliable type of single-phase motor which can accommodate itself to the severe and varying demands of traction service. Apart from the single-phase induction motor, which is out of the question on account of its inherently poor starting characteristics, only the single-phase commutator motor remains for consideration. And the latter, in turn, cannot be constructed as a sufficiently large power unit in the case of a 50-cycle supply, because the difficulty in commutating heavy currents increases rapidly with the supply frequency.

Here again, however, the application of the grid-controlled rectifier has in recent years led to a practical solution of the problem, in the form of a rectifier locomotive incorporating alternating-current motors of a rather special type operating at frequencies lying between 40 and 60 cycles per second. In the direct-current rectifier locomotive discussed in the previous section, the function of the rectifier was simply that of changing the alternating current delivered at the overhead conductor to direct current for supply to the traction motors. But in the case of the *alternating-current rectifier locomotive* the function of the rectifier is to replace the commutator of a series-type alternating-current traction motor. How this is accomplished is not immediately evident from such a simple statement. But if it is considered that the action of brushes and commutator is in effect that of a group of switches, each of which momentarily connects the "active" part of the armature winding to the motor terminals, then it is clear that the operation of the motor as a whole is in no way affected by allowing a suitably controlled rectifier to exercise this purely switching function. Once this fundamental principle is realized, the development of a practical alternating-current motor operating on these lines is not a matter fraught with any appreciable difficulty.

Consider, in the first place, a direct-current motor in which each armature coil is connected not to a commutator bar but to an electric valve, such as a single-anode or half-wave rectifier. In view of space limitations such a multiplicity of valves could not possibly be accommodated on the motor shaft along with the armature, but would have to be fixed. Consequently the armature would also have to be fixed. This implies, in turn, that the field winding would have to rotate. We thus arrive at an arrangement in which the armature becomes the *stator*, the field winding becomes the *rotor*, and the commutator is replaced by a series of electric valves or half-wave rectifiers. To all outward appearances such a machine would be identical with a synchronous motor.

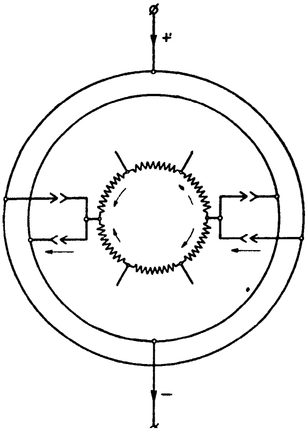

FIG. 107. VALVE-CONTROLLED MOTOR WITH CLOSED WINDING

Elektrische Bahnen

Now in the case of a commutator motor each commutator bar serves alternately to lead in and to lead out the motor current to and from the armature winding. Referring this principle to the new type of motor implies that each tapping on the armature winding to which a commutator bar is normally connected would now have to be connected to two valves, one for each direction of current flow, as shown in Fig. 107. To overcome this difficulty the closed or ring winding of Fig. 107 may be replaced by an open or star winding in which individual sections are displaced in phase with respect to one another and come into action successively, one at a time. Provided these sections are suitably distributed around the stator such an open winding will differ but little in its electromagnetic action from a conventional closed winding, even when the direct current enters or leaves the winding at one point only, viz. the star point. In this way the comparatively simple arrangement of Fig. 108 is obtained, in which a multiple-anode rectifier of normal type can be employed. The requisite control of the current distribution throughout the stator winding is then conveniently obtained by grid control of the rectifier, the control gear taking the form of an impulse distributor either mounted on or driven from the rotor shaft. The fundamental circuit diagram of such a rectifier-controlled direct-current motor is given in Fig. 109. The grid-control gear allows the stator current to commutate from phase to phase in such a way that the magnetic axis of the stator field rotates in synchronism with that of the rotor. In other words, if the rotor moves through a certain angle under the influence of a load torque then the grid-control gear (impulse distributor) rotates through a corresponding angle, and, by its action on the rectifier, alters the phase position of the magnetic axis of the stator winding in such a way as to bring it into line once more with the magnetic axis of the rotor. In this way electrodynamic equilibrium of the motor is maintained under all conditions of load and speed.

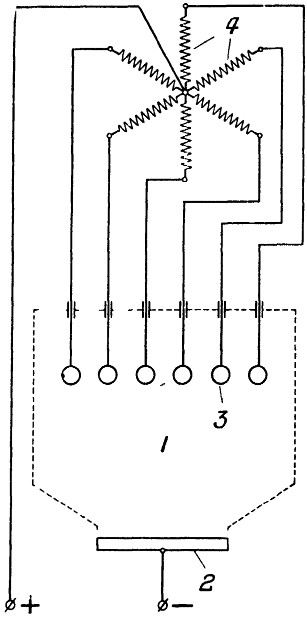

FIG. 108. VALVE-CONTROLLED MOTOR WITH OPEN WINDING

1 = Multi-phase electric valve
2 -- Cathode
3 = Anodes
4 - Stator winding of motor

Elektrische Bahnen

Such a rectifier-controlled motor nevertheless still labours under two disadvantages. Firstly, starting resistances are necessary as in the ordinary commutator motor; and, secondly, a source of commutating e.m.f. must be provided to commutate the direct-current arc from anode to anode during the period in which the motor is started and run up to speed. The latter difficulty can be overcome by supplying the motor with a strongly pulsating direct current; and a little consideration will show that this requirement can readily be met by employing two stator windings, each fed from one secondary phase of a single-phase supply transformer. In this way, although use is made of an alternating-current supply, each stator winding is in effect traversed by a continuous current pulsating between zero and a maximum, the pulsations being 180

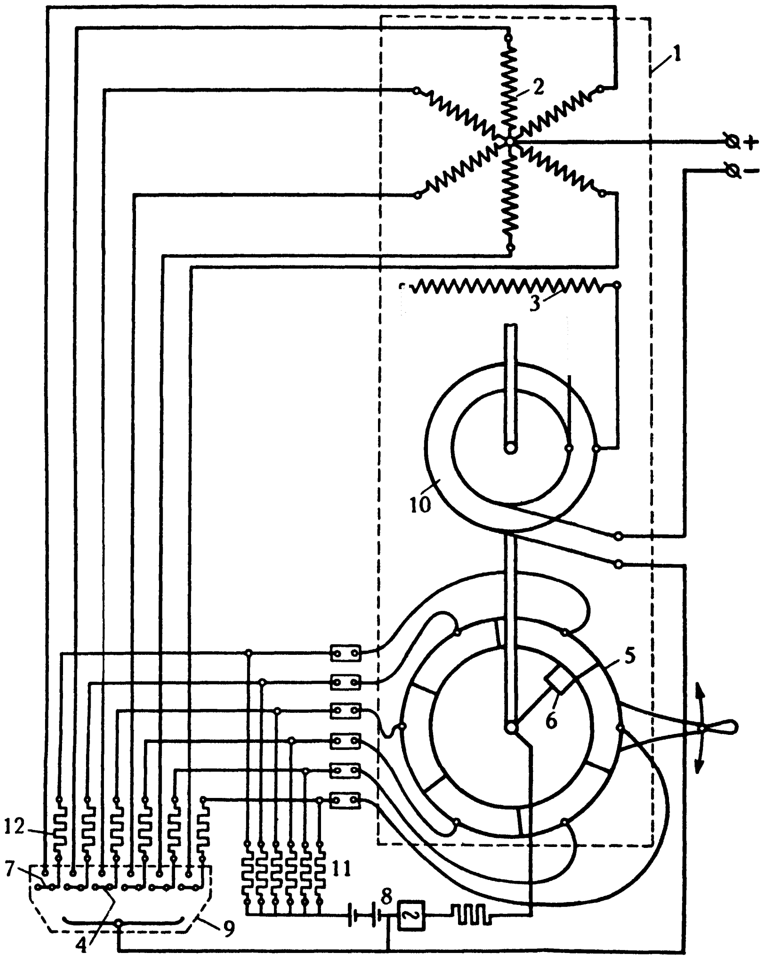

Fig. 109. Circuit Diagram of Rectifier-controlled Direct-current Motor (Brown-Boveri et Cie.)

1 = Motor
2 = Stator winding
3 = Rotor winding
4 = Control grids
5 = Impulse distributor
6 = Rotating brush

7 = Anodes
8 = Grid excitation supply
9 = Rectifier
10 = Rotor slip-rings
11 and 12 = Grid circuit and limiting resistors

Elektrische Bahnen

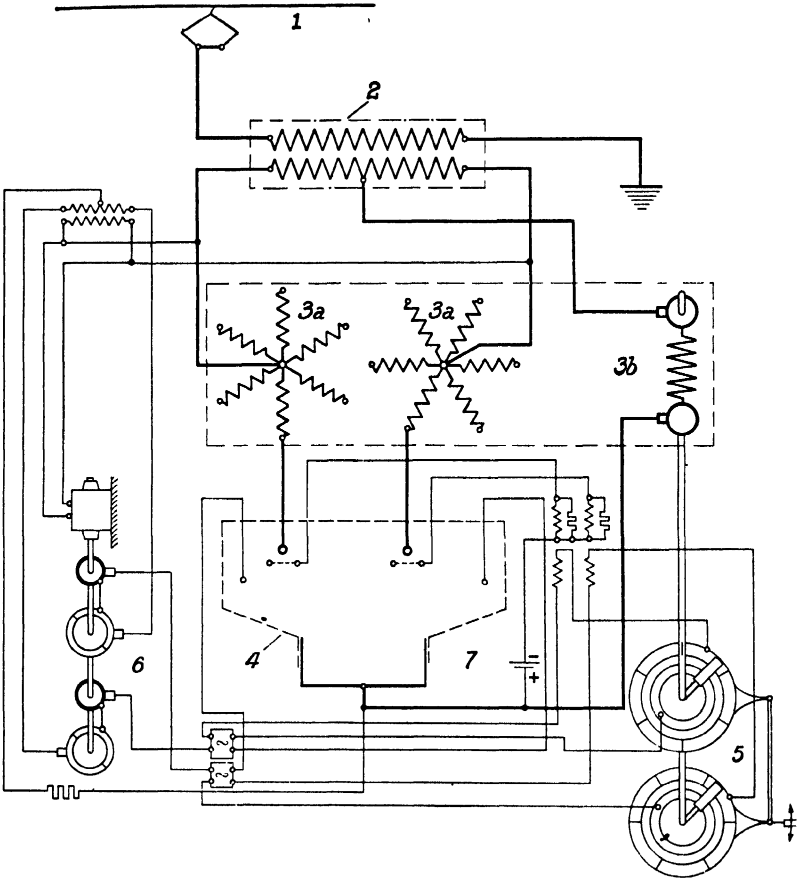

FIG. 110. SCHEMATIC DIAGRAM OF ALTERNATING-CURRENT RECTIFIER LOCOMOTIVE (BROWN-BOVERI ET CIE.)

1 = Overhead conductor
2 = Supply transformer
3a = Stator windings
3b = Rotor winding
4 = Grid-controlled rectifier
5 Impulse distributor
6 and 7 = Grid excitation supply

Elektrische Bahnen

electrical degrees out of phase in the two windings. The final arrangement of such a motor, embodied in the alternating-current rectifier locomotive, is illustrated diagrammatically in Fig. 110. In view of the symmetry of this arrangement the supply transformer operates as a normal single-phase rectifier transformer, whilst the stator windings, whose corresponding

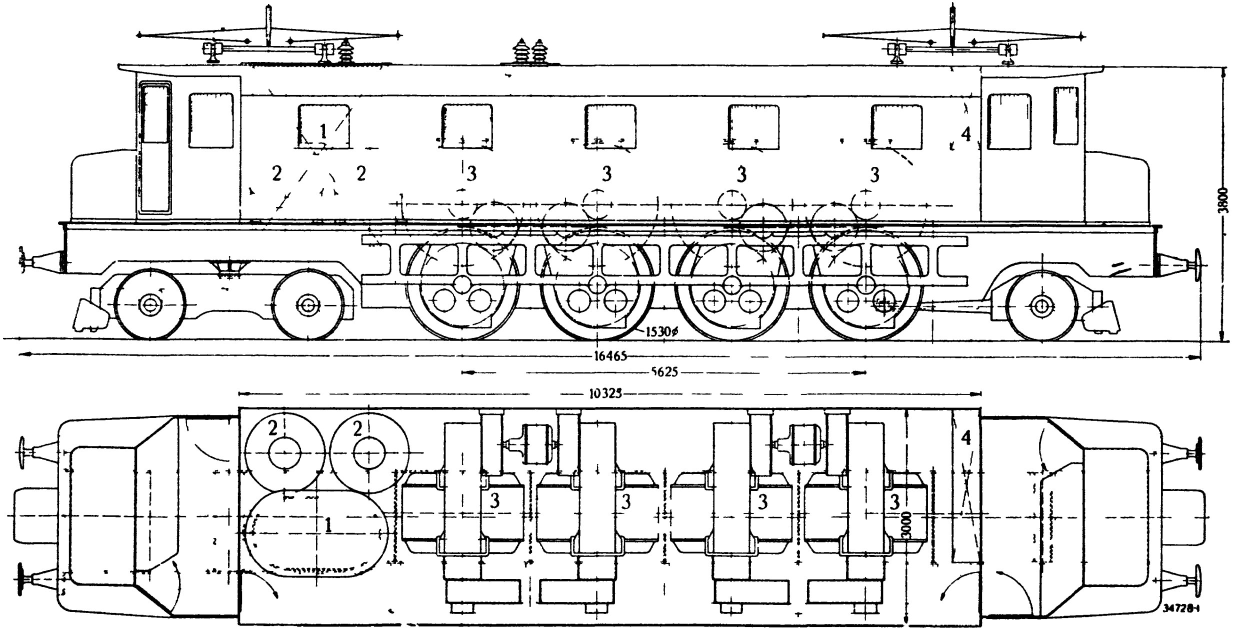

FIG. 111. 3 200-H.P , 15 000-VOLT SINGLE-PHASE PASSENGER LOCOMOTIVE CONVERTED TO RECTIFIER CONTROL (BROWN-BOVERI ET CIE)

Elektrische Bahnen

phases deliver current during alternate half-cycles, operate so as to supply direct current to the rotor winding. Consequently, the alternating-current rectifier locomotive is independent of frequency in that the traction motor is, in effect, a commutatorless direct-current machine having series characteristics. The arrangement of Fig. 110 also overcomes the first difficulty referred to above, namely, that of limiting the starting current. In so far as each pair of simultaneously operating stator phases constitutes a full-wave rectifier system, the output voltage, and therewith the motor current, can be regulated in the usual manner by retarding or advancing the instant of arc commutation. Hence as far as power factor conditions at starting are concerned, the alternating-current rectifier locomotive behaves in the same way as its simple direct-current prototype *without* neutral-point anode and multiple-voltage anode connection.

A practical example of the alternating-current rectifier locomotive is illustrated in Fig. 111, which depicts a high-speed passenger locomotive of the standard 2–Do–1 type employed by the Swiss Federal Railways converted to this new method of operation. The locomotive is shown equipped with commutatorless motors of the same output as the standard single-phase machines, viz. 800 h.p. on a 1-hour rating. The alternating-current supply is at 15 000 volts and 50 cycles per second. Calculations have shown that no increase in either weight or capital cost is involved by the conversion. The normal 16⅔-cycle transformer is just as heavy as the 50-cycle transformer together with the two grid-controlled rectifiers, whilst the extra weight of the commutatorless motors is offset by the saving in weight on the control gear. Furthermore, the savings in capital cost due to the lighter transformer and the absence of on-load tap-changing gear and contactor gear, as well as of the commutators on the motors, are just sufficient to pay for the grid-controlled rectifiers together with their associated apparatus.

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CHAPTER XI

THE MERCURY-ARC INVERTOR

The mercury-arc current convertor is essentially a polarized device, in that current can flow through it in one direction only. At first sight the acceptance of this axiom would seem to point to the conclusion that the direction of energy flow in a device of this kind must of necessity be irreversible also. Long association with converting plant of a purely electro-dynamic nature has led to the habit of regarding a return of energy from the direct-current side to the alternating-current side of a convertor as being bound up with the conception of current reversal. On closer consideration of the principles involved, however, it will become apparent that such a habit of thought arises from a narrow and quite erroneous line of reasoning. Fundamentally, electric power is a product of current and voltage. It is therefore clear that a reversal of energy flow can be brought about by reversing the voltage while the direction of current flow is maintained.

Thus in the case of the mercury-arc current convertor the return of energy from the direct-current system to the alternating-current network—a process which has come to be known as the *inversion* of direct to alternating current—is possible if the current arc can establish itself at the several anodes in those instants in which the respective anode voltages are negative. This necessitates the reversal of the connections on the direct-current side of the apparatus, together with the use of grid control to force the commutation of the current arc. In other words, the current convertor must operate in such a manner that the establishment of the current arc at a particular anode is delayed (by means of the grid-control gear) until such time as the e.m.f. supplied by the direct-current system is opposed to, and, at the same time, somewhat greater than, the instantaneous voltage of the corresponding secondary transformer phase. Under these circumstances the preponderance of the direct-current driving e.m.f. over the back e.m.f. in the secondary phase of the transformer results in a flow of current which is in the normal direction through the current convertor, but which is opposed to the instantaneous voltage of the transformer secondary. The latter condition constitutes a reversal of energy flow in the transformer element of the current convertor as compared with the corresponding condition during rectification.

Polyphase Inversion of Direct to Alternating Current. The behaviour of such a current convertor when functioning firstly as a *rectifier*, and secondly as an *invertor* may be understood by a reference to Fig. 112.* Diagram (*a*) illustrates the by now familiar process of rectification and shows the transformer secondary delivering an anode voltage E between the neutral point O and the anode terminal A. This voltage has to overcome the arc drop ε in the rectifier and the counter e.m.f. V of the direct-current load circuit before it can drive a current I through the load. During those portions of the anode voltage-cycle in which E is increasing, the current I increases since the other circuit voltages V and ε remain unchanged, so that there is then no tendency for the current arc to transfer itself to the next anode in the phase sequence. Only when the anode voltage E_1, and therewith the load current I, commences to decrease and the voltage E_2 of the next anode commences to increase, does the arc commutate from anode 1 to anode 2. Commutation takes place at the instant corresponding to the point of intersection of the anode voltages E_1 and E_2.

When energy return is required from the direct-current circuit, through the current convertor to the alternating-current system the voltage conditions are approximately as shown in diagram (*b*) of Fig. 112. The load current I cannot change its direction, and hence the connections to the direct-current circuit must be changed over. The direction of the circuit voltages V and ε will remain unchanged, but that of the anode voltages E must now be reversed, that is in opposition to the current I. In the case of the invertor, then, the combined voltages E and ε have first to be overcome by the direct-current supply voltage V before current can be made to flow through the invertor. From the diagram it is seen that the positive pole of the direct-current supply is now connected to the neutral point of the transformer, instead of to the cathode of the current convertor. In other words, when it is desired to invert direct to alternating current it is necessary to reverse the polarity of current convertor in relation to the

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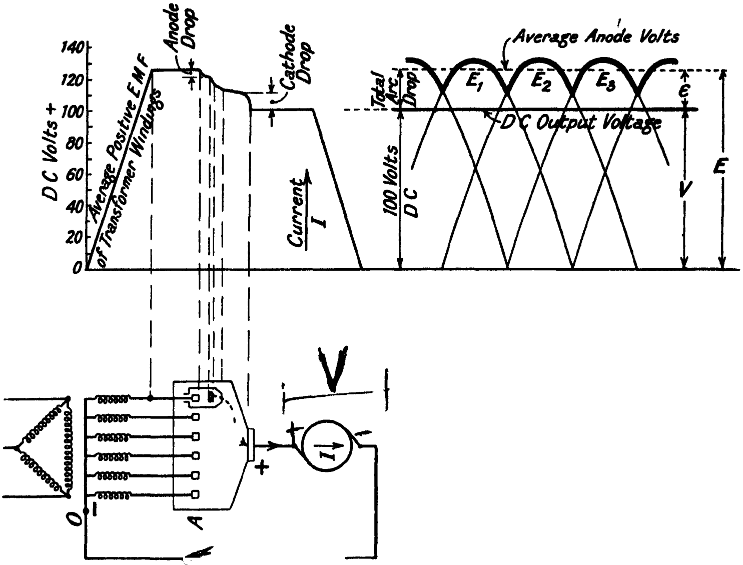
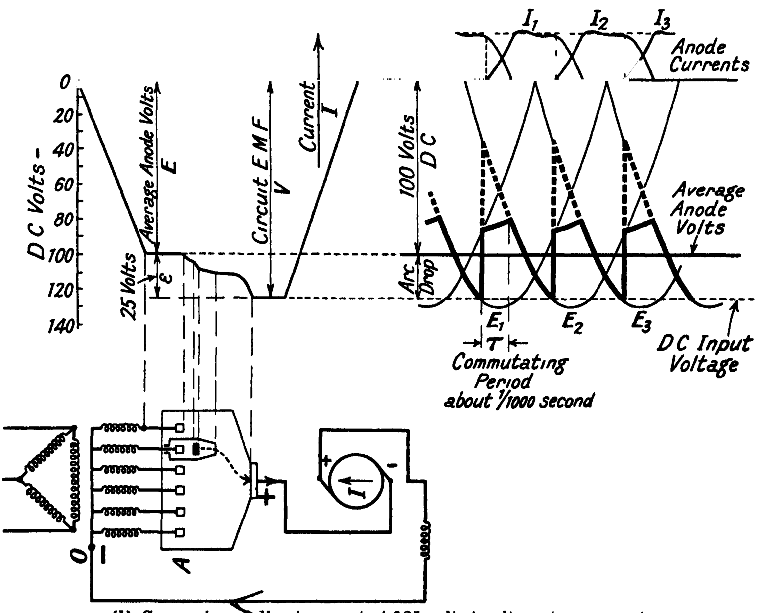
* The author is indebted to Mr. J. E. Calverley for this method of representing the circuit conditions.



(*a*) Conversion of alternating current to direct current at 100 volts



(*b*) Conversion of direct current at 125 volts to alternating current

FIG. 112. VOLTAGE CONDITIONS IN POLYPHASE CURRENT CONVERSION

direct-current system in addition to "reversing" the grid control, i.e. increasing the *ignition angle* from the value α to the value $(2\pi - \alpha)$. Referring to diagram (*b*), it is seen that during inversion the current I decreases as the value of E becomes more negative, and increases as E becomes less negative, which are the reverse of the conditions obtaining during rectification.

When transmitting power in either direction through the current convertor, stable operation can only be achieved when the current arc commutates from one anode to the next at an instant in which the anode carrying the decreasing current is at a lower potential relative to that of the anode to which the current arc is just to be transferred. In other words, commutation is only possible at instants in which the relative potential difference between the anodes is in the requisite direction to effect the current transfer. During the conversion of alternating to direct current this occurs naturally as a consequence of the anode-voltage sequence. When the apparatus is operating as an invertor, however, the negatively increasing anode voltage, which now constitutes the back e.m.f. of the circuit, is utilized to cause the decrease in current which precedes commutation. The arc is extinguished at anode 1, for example, as soon as the anode voltage E_1 attains the same value as the input voltage of the direct-current circuit. At this instant anode 2 is still at a relatively higher potential, so that commutation can be effected by momentarily applying a positive potential to its grid, which is, of course, normally negative. Anode 2 now carries the current which then decreases similarly. In the meantime, the voltage E_1 of anode 1 reaches and passes its negative maximum and then again attains the same value as the input voltage of the direct-current circuit. At this instant there is a tendency for the arc to transfer back again to anode 1, since the relative voltage is in the direction requisite to such transfer. It is prevented from doing so, however, by the fact that the grid of anode 1 has in the meantime reverted to its normal state of negative potential, so that no arc can be established.

From these considerations, it will be appreciated that *inversion is only possible with the aid of grid control.* The control grids are necessary not only to determine the successive instants of arc ignition, but also to prevent re-ignition of the arc at subsequent and unsuitable points in the anode-voltage cycle. In the case of normal rectification a natural commutation of the arc takes place in the region of positive anode voltage. With rectification at reduced voltage by grid control (diagrams (*a*) and (*b*) of Fig. 113) commutation still takes place in the region of positive anode voltage, but is forced, while in the case of inverted operation of the rectifier (diagrams (*d*) and (*e*) of Fig. 113) forced commutation of the arc from anode to anode takes place in the negative region of anode voltage. At this stage it is as well to point out that the mercury-arc current convertor, when operating as an invertor in the above manner, cannot generate an alternating-current voltage in the sense that it can produce a continuous voltage by simple rectification of sinusoidal alternating voltages. The invertor requires, in addition to the suitable excitation of its control grids, an opposing voltage of fixed frequency. This back e.m.f. is generally provided either by an available alternating-current power system or by a synchronous machine operating as a frequency fixer. The frequency fixer may be either an alternator, or a synchronous motor or condenser provided with a starting motor taking power from the direct-current supply. As soon as the frequency fixer has run up to speed, and delivers an opposing voltage to the invertor, the starting motor can be shut down, since the frequency fixer then receives its driving power directly from the invertor.

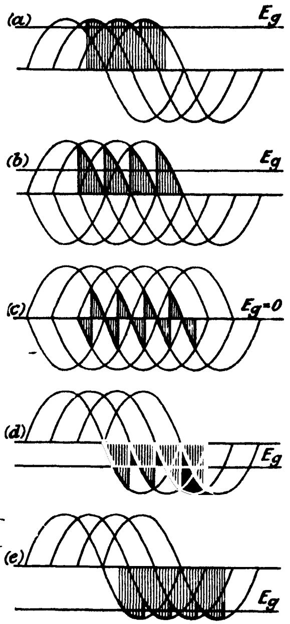


FIG. 113. PHASE COMMUTATION IN A GRID-CONTROLLED CURRENT CONVERTOR

(*a*) and (*b*) = Rectification at reduced voltage
(*c*) = Condition of zero output voltage
(*d*) and (*e*) = Inversion at reduced voltage

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When the mercury-arc invertor supplies power to an energized alternating-current system, the frequency of the invertor set is fixed and equal to that of the power system. The inversion of direct to alternating current is in such case said to be *predetermined.* In the other type of invertor, discussed above, the frequency is a function both of the field excitation of the synchronous machine and of the grid excitation of the current convertor. If the frequency fixer is a synchronous motor, its speed can be varied within wide limits by altering its excitation and by varying the angle of arc ignition in the current convertor. In the case of mercury-arc invertors of this type, the inversion process is generally referred to as being *self-determined.*

Current-convertor Control of Reversing Direct-current Drives.

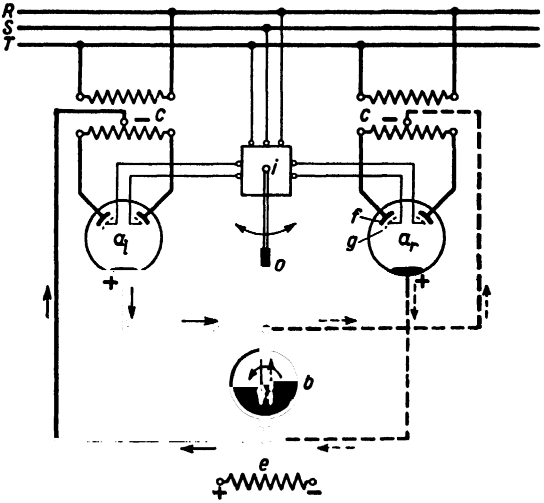

FIG. 114. CIRCUIT DIAGRAM OF A STATIC WARD-LEONARD SET

a_l, a_r - Current convertors
b - D.C. machine
c = Supply transformer
e = Field winding
f = Anode
g = Control grid
i = Grid-control apparatus
o = Control lever

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Investigations have proved that inversion of direct to alternating current in the manner just described can in practice be effected over the entire load and voltage range of the current convertor; that is to say, by making use of the voltage-regulating properties of grid control, the average anode voltage can be varied even when the apparatus is operating as an invertor. Thus, in the case of a motor load connected on the direct-current side of such a current convertor, regeneration can take place practically down to the standstill condition of the load.

This important feature of the grid-controlled current convertor leads at once to the arrangement of a tandem conversion unit, for controlling the speed and direction of rotation of a direct-current motor, which is analogous in its operation to the conventional Ward-Leonard arrangement of a motor-generator or rotary convertor. The skeleton circuit diagram of such a "static Ward-Leonard set" is shown in Fig. 114. With this arrangement the motor-generator or rotary-convertor unit is replaced by two grid-controlled rectifiers a_l and a_r supplied, through transformers *c*, from the alternating-current system, and connected "back-to-back" on the direct-current side. The motor whose speed and running direction is to be controlled has its armature *b* connected across the direct-current output bus-bars, whilst its field *e* is separately excited from some convenient source of direct-current supply, such as an ordinary rectifier unit. Cross-connection of two rectifiers on the output side in this way is made possible by the correct operation of the grid-control apparatus *i*, which functions so that only one rectifier at a time is allowed to pass current. Should, by any chance, both rectifiers come into operation simultaneously, then a heavy short-circuit current would immediately circulate between them, a condition fraught with possible danger to the installation. For this reason particular care has to be exercised in the choice and design of suitable grid-control apparatus. It is fairly evident that some form of impulse system of grid-control is essential if accuracy of ignition-angle control and, therewith, stability of operation under conditions of varying load and voltage are to be obtained.

The type of grid-control system most favoured is that making use of a synchronously-driven impulse distributor in conjunction with a direct-current source of grid excitation. The general principles underlying the operation of this method of impulse control were dealt with in Chapter IX, whilst its application to the control of a "reversible" mercury-arc current convertor is illustrated in Fig. 115. In the case of the static Ward-Leonard arrangement of Fig. 114, the grid-control apparatus comprises two impulse distributors driven by a common synchronous motor; and the control lever is coupled to both contact discs in such a way that these are phase-displaced in opposite senses.

(*a*) RECTIFIER OPERATION—MOTOR RUNNING. During rectifier operation only the positive half-waves of anode voltage are utilized, as it is only during such times that the individual anodes are positive with respect to the cathode. Normally, in a polyphase rectifier system, each anode carries current as long as its potential is higher than that of the cathode. But the presence of inductance, e.g. smoothing chokes or the armature of a motor, in the direct-current circuit may alter the circuit voltage conditions to quite a considerable extent due to energy storage in the inductance. In this case the instantaneous value of the driving e.m.f. in the direct-current circuit is no longer equal to the alternating voltage applied to the anode, but becomes greater or less according to the current-change taking place in the inductance. Consequently it is possible for an anode to continue carrying current even when its potential has become negative with respect to the cathode, as shown in Fig. 116 (*a*). Here the e.m.f. induced by the current-change in the inductance overcomes the already negative anode voltage

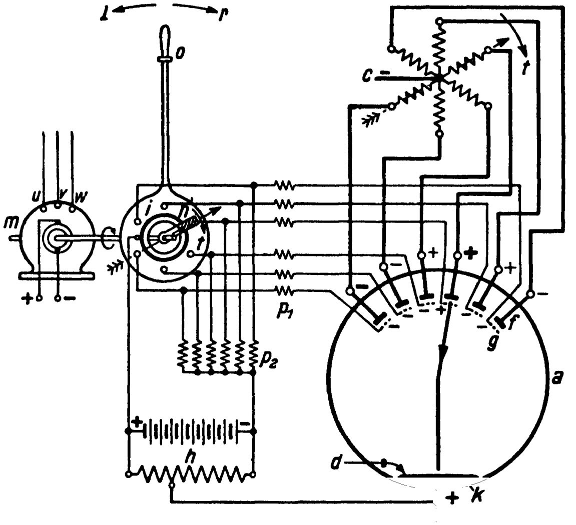

FIG. 115. IMPULSE CONTROL WITH DIRECT-CURRENT GRID EXCITATION

a = Current convertor
c = Transformer secondary
d = Excitation arc
f = Anode
g = Control grid
h = Grid supply potentiometer
i = Contact disc
k = Cathode
m = Synchronous driving motor
n = Rotating brush arm
o = Control lever
p_1, p_2 = Grid-current limiting resistances
t = Time axis
u, *v*, *w* = Driving motor terminals

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and provides the driving e.m.f. necessary for maintaining the arc.

If the rectifier is operating against a back e.m.f. V (Fig. 117 (*a*)), then the driving e.m.f. is reduced by this amount from E_a to E_d, and each anode will then carry current only so long as the residual driving e.m.f. exceeds the arc drop ε. For the sake of simplicity no account has been taken in this diagram of any inductance also present in the direct-current circuit. When the instant of arc ignition is chosen so that the anode voltage is just approaching zero, the mean value of the rectified voltage is small, as may be seen from Fig. 116 (*a*). On the other hand if the instant of arc ignition is advanced—for example, by moving the control lever *o* of Fig. 115 in the direction of the arrow *l*—then the output voltage can gradually be raised until the maximum value is reached, as shown in Fig. 116 (*b*). A separately-excited direct-current motor supplied from such a grid-controlled rectifier can thus be started from rest by moving the control lever *against* the direction of rotation of the impulse distributor, and allowed to attain full speed. In the case of two such rectifiers cross-connected on the direct-current side, as shown in Fig. 114, when the motor is brought up to speed in a given direction by one rectifier the other rectifier is rendered inoperative. The motor can similarly be started from rest, and made to gather speed in the

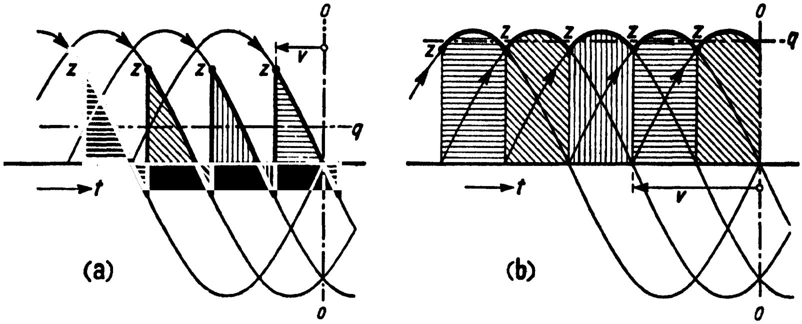

FIG. 116. VOLTAGE CONDITIONS

(*a*) Voltage conditions with delayed arc ignition
(*b*) Voltage conditions with arc ignition fully advanced

o = Zero-voltage ignition position
v = Angle of advance of arc ignition $\left(\frac{\pi}{2} - \alpha\right)$
z – Successive ignition instants
q = Mean rectified voltage
t = Time axis

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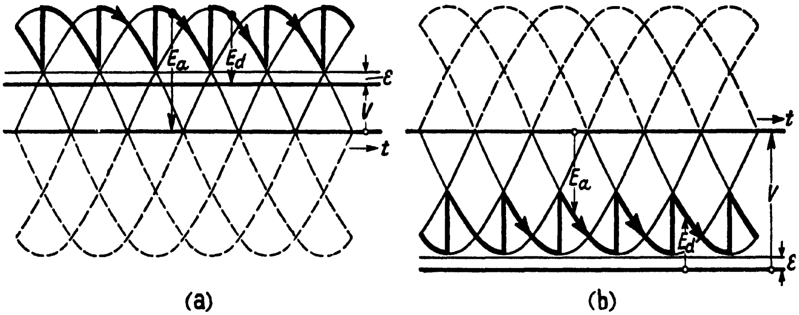
opposite direction, by reversing the movement of the control lever. This action retards the ignition angle of the first rectifier beyond the zero-voltage position, and the rectifier thus becomes inoperative. At the same time the ignition angle of the second rectifier gradually advances from the zero-voltage position until the motor reaches full speed. It is seen, therefore, that during rectifier operation only one current convertor at a time functions so as to impress its output voltage on the motor, these voltages being in opposition. The direction of rotation of the motor then depends upon which current convertor is brought into operation by the control lever.



(a) (b)

FIG. 117. CURRENT CONVERTOR OPERATION

(*a*) Rectifier operation against back e.m.f.
(*b*) Invertor operation due to back e.m.f.

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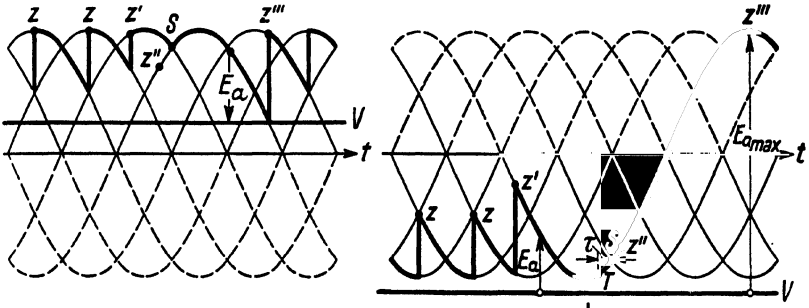
(*b*) INVERTOR OPERATION — MOTOR REGENERATING. As mentioned above, the current convertor which at the moment is not operating as a rectifier also comes under the influence of the grid-control apparatus. But its ignition angle is delayed *beyond the zero-voltage position* (Fig. 117 (*b*)), so that the blocking action at the anodes is removed when the anode voltages are negative. As the result, the current convertor tends to operate as an invertor in the manner described earlier on in the present chapter. At first no ignition of the current arc takes place because the driving e.m.f. is negative. Inversion can only commence when the back e.m.f. V of the direct-current circuit exceeds the anode voltage E_a in magnitude. If this condition is satisfied then a driving e.m.f. E_d is established which is sufficient to neutralize the e.m.f. generated in any circuit inductance and overcome the arc drop ε, and thus to drive a current through the rectifier in the normal direction from anode to cathode. This current is in the same direction as the back e.m.f. V of the direct-current circuit, but is *opposed* to the direction of the anode voltage E_a. Such a condition denotes the supply of energy to the alternating-current system. In the particular case which we are here considering, where the back e.m.f. V originates in a direct-current machine, this condition of energy reversal simply means that the machine is operating as a generator, i.e. the motor is regenerating. The magnitude of the regenerated current depends on the excess of the e.m.f. in the direct-current circuit over the anode voltage—that is, upon the surplus driving e.m.f. available for overcoming the arc drop plus the circuit impedances.



(a) (b)

FIG. 118. IRREGULARITY OF ARC IGNITION DURING (*a*) RECTIFICATION AND (*b*) INVERSION

τ = deionizing time

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In the case of rectifier operation it is as a rule immaterial whether arc ignition takes place somewhat too early or somewhat too late. Referring to Fig. 118 (*a*), if Z, Z indicate the normal instants of arc commutation and if, due to some fault in the grid impulse distributor, for example, the arc is established at any anode at the instant indicated by Z' in the diagram, the effect is merely to increase momentarily that particular anode's contribution towards the available driving e.m.f. in the circuit. The result is a momentary increase in the current supplied to the motor. If the ignition impulse is applied so early in the cycle (Z'') that the voltage of that particular anode is still below that of the anode immediately preceding it in the firing sequence, arc ignition cannot take place until the instant in which both anode voltages are the same, as indicated at S in Fig. 118 (*a*). On the other hand, if arc ignition takes place later than normal (Z''') the effect is a momentary reduction in the driving e.m.f., resulting in a momentary decrease in current.

The corresponding conditions are somewhat different in the case of invertor operation, as may be seen from Fig. 118 (*b*). Should arc ignition take place too soon, as indicated at Z' in the diagram, the current is commutated at an instant in which the back e.m.f. of the alternating-current system still has a low value. As the result, the driving e.m.f. in the circuit may become momentarily very large, so that the current may assume a very high instantaneous value. On the other hand, should the ignition impulse occur too late (Z'') a condition arises in which the instantaneous voltage of the anode already carrying current has in the meantime become less than that of the anode to which the arc is to be transferred. Consequently the second anode is no longer in a position to pick up the arc and the first anode continues to carry the current, the driving e.m.f. increasing all the while. Eventually a point is reached, indicated at Z''' in the diagram, where the driving e.m.f. is no longer the difference between the direct-current circuit e.m.f. V and the alternating-current back e.m.f. E_a, but is equal to their sum, and where the instantaneous current in the circuit may reach a dangerously high value as the result. It will be appreciated, therefore, that the grid-control gear must at all times function so as to establish ignition of the arc at an instant (T) determined by the requirement that it leaves sufficient time for the preceding anode to be blocked by the reapplication of a negative grid potential. This requirement is met if the time interval between T and S—the latter being the latest instant in which arc commutation is still theoretically possible—exceeds the time necessary for deionization of the arc-discharge path. It is thus essential to stable operation of the mercury-arc invertor that some impulse system of grid control be employed.

(*c*) ALTERNATE RECTIFIER AND INVERTOR OPERATION. In the application of a tandem current-convertor unit (such as that shown diagrammatically in Fig. 114) to the control of a reversing direct-current motor, it must be remembered that the individual current convertors are mutually exclusive in their operation. And in consequence of their being connected "back-to-back" each current convertor corresponds to one direction of rotation of the machine, because the driving torque is determined by the flow of current through the armature.

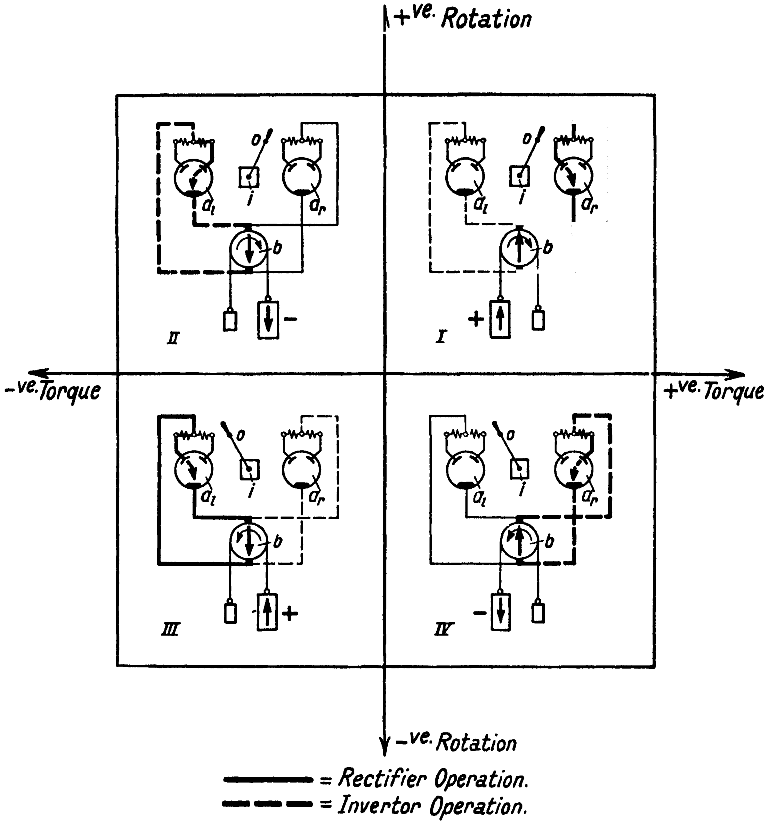

Fig. 119. Control Diagram of Static Ward-Leonard Set

a_r, a_l = Current convertors
b = Direct-current motor
i = Grid control gear
o = Control lever

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The several operating conditions are indicated in the control diagram of Fig. 119. The upper quadrants refer to clockwise rotation, the lower to anti-clockwise rotation of the motor. Similarly, the right-hand quadrants relate to operation of the right-hand current convertor a_r (grid-control lever o thrown to the right), whilst the left-hand quadrants correspond to operation of the left-hand current convertor a_l (grid-control lever *o* thrown to the left). The horizontal axis of the diagram indicates the motor torque (current), and the vertical axis the direction of rotation (voltage). With clockwise rotation and positive torque (Quadrant I) the direct-current machine functions as a motor, as it does also in the case of negative torque and anti-clockwise rotation (Quadrant III). On the other hand, if the torque and direction of rotation are in opposite directions the machine functions as a generator, that is, regenerative braking of the motor takes place (Quadrants II and IV). By moving the grid-control lever from the extreme right to the extreme left the current convertors follow the operating sequence given by traversing the quadrants of the control diagram in the order I–II–III–IV.

The operating characteristics of such a static Ward-Leonard set are shown in Fig. 120. The equipment* comprises two six-phase glass-bulb rectifiers supplying a rolling-mill motor of 110/170 kW output at 500 volts, the motor driving a strip mill at 1 000 r.p.m. The twin rectifier unit is fed from the 440-volt, three-phase, 50-cycle works supply through a transformer with two secondary windings connected on the double three-phase system. This explains the non-linearity of the characteristics in the vicinity of the zero-current axis. Experience has shown that the operation of such a tandem current-convertor unit is in every way the equal of a conventional Ward-Leonard set. In particular the smoothness and continuity of control over the entire speed range, and in both directions of rotation, obtained by means of grid control is strictly comparable with that associated with the corresponding rotating type of plant.

Regenerative Operation of Traction Rectifier Substations. A valuable feature of the static inversion of direct to alternating current is the facility with which rectifier equipment can be adapted to meet the special requirements of direct-current traction systems in which a large proportion of the energy supplied to the electric tractor—whether locomotive, motor coach, tramcar or trolley bus—is returned to the substations when regenerative braking is employed after coasting periods or in the descent of long grades.

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* Installed in the Gartenfeld works of Messrs. Siemens-Schuckert Werke A.G., Berlin, in 1932. Early in 1934 this firm supplied a further static Ward-Leonard equipment for a large rolling mill in South Africa. As far as the author is aware these two are the only installations of this type in operation.

The method of regenerative control as used to decelerate a direct-current motor preparatory to reversing its direction of rotation, and described in the preceding section, is characterized by the fact that, as the motor slows down, the back e.m.f. of the invertor is continually reduced to an extent leaving just sufficient driving e.m.f. in the invertor circuit to allow an adequate braking current to flow through the armature of the motor. In other words, regeneration is allowed to take place till the motor is at a standstill and its voltage consequently zero. In the case of a traction load, however, it is necessary to maintain the voltage at the substation reasonably constant, that is, within plus or minus 10 per cent of the nominal voltage of the traction system. During regenerative braking the traction motor functions as a generator and its voltage tends to rise above that of the system, and, in practice, a 10 per cent rise in volts is usual under this condition of operation.

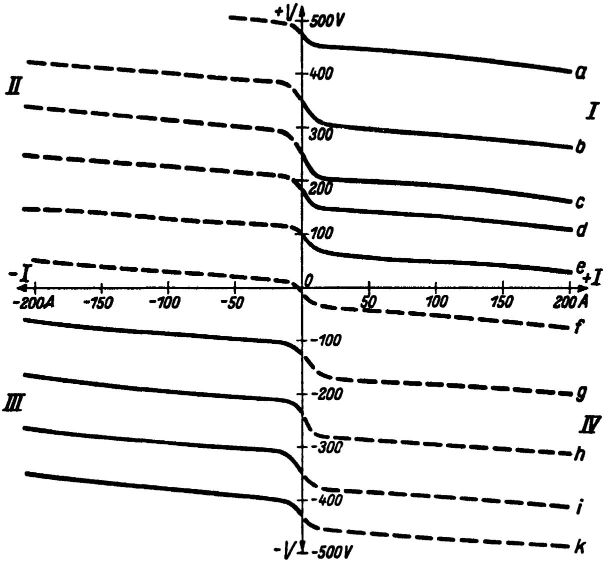

FIG. 120. OPERATING CHARACTERISTICS OF STATIC WARD-LEONARD SET

Characteristic	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*k*
Ignition angle	29	51	64	72	81	94	105	117	129	140

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A further characteristic of regenerative control in this case is the fixed polarity of the traction system. In conseqence of this factor regenerative operation of a rectifier substation can only be achieved by reversing the polarity of the rectifier, since current-reversal is fundamentally impossible. An alternative solution which presents itself in the case of tramway and trolley-bus systems, where the diversity of the load is such that the amount of energy to be regenerated is only a fraction of the substation output, consists in the provision of a small invertor unit connected permanently to the substation bus-bars, and arranged to come into operation as soon as the bus-bar voltage exceeds a certain predetermined figure—usually from 5 to 10 per cent above the normal voltage of the system. In considering main-line electric railway systems, on the other hand, the comparative infrequency of the service combined with the negotiation of heavy gradients may give rise to a situation in which the return of energy is at times equal to the full output of the substation at other times. To cater for this condition the rectifier equipment must be so designed as to be capable of handling the flow of the full amount of power in either direction.

A type of rectifier substation which has been employed with some measure of success by the Italian State Railways for their 3 300-volt direct-current traction systems is that making use of a single grid-controlled steel-tank rectifier unit, together with appropriate switchgear and control gear for reversing its polarity. A typical scheme of this kind is shown in Fig. 121 in which the rectifier *A* is shown supplied from the e.h.t. bus-bars through a transformer *E*, and connected to the direct-current bus-bars through reversing contactors *K* and a high-speed circuit-breaker *L*. The grid-excitation equipment is of the usual direct-current impulse type, comprising an impulse distributor *C* driven by a synchronous motor *F* fed from the e.h.t. bus-bars *via* the small transformer *G*.

To obtain regenerative working of the rectifier it is necessary for the following sequence of operations to be made, dependent on a rise of bus-bar voltage of, say, 10 per cent persisting for a definite period of time—

1. Disconnection of the rectifier unit from the direct-current bus-bars by opening of the high-speed circuit-breaker.

2. Reversal of the polarity of the rectifier with reference to that of the traction system by means of the reversing contactors.

3. Adjustment of the grid-control gear in accordance with invertor operation, in place of rectifier operation.

4. Reconnection of the rectifier unit to the direct-current bus-bars by closing of the high-speed circuit-breaker.

In order to obviate the possibility of mal-operation it is necessary to provide interlocks so that the reversing contactors cannot effect the polarity reversal until the high-speed circuit-breaker has opened, and, similarly, so that the latter cannot be closed until the reversing contactors have operated. The initiation of the operating sequence is effected by a master relay whose function must also be to determine the correct sequence in terms of certain circuit constants which are characteristic of the service conditions. In other words, to ensure polarity reversal of the rectifier unit at the correct moment, the operation of the master relay must be dependent upon some electrical characteristic of the traction system. It is of little use to make the action of this relay dependent upon the direct current attaining zero value if there is no means of

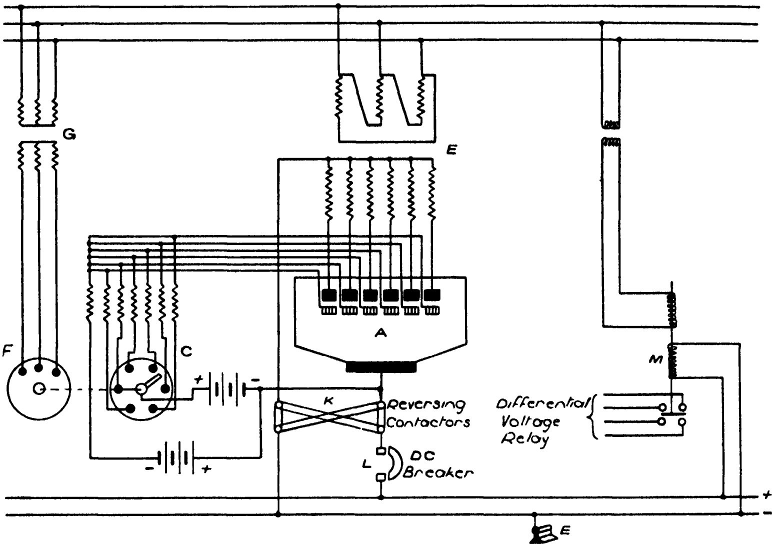

Fig. 121. Fundamental Circuit Arrangement of a Reversible Rectifier Unit

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ascertaining what will be the direction of energy flow immediately afterwards. On the other hand, the bus-bar voltage is determined directly by the demand for energy, or by the surplus of energy available on the part of the traction system. At the same time it is determined also by the voltage of the e.h.t. system to which the rectifier system is connected. For these reasons, then, it is essential to employ as a determining factor in the operation of the master control relay (indicated at *M* in the diagram) a quantity which does not depend merely upon a comparison of the voltage of the traction system with a certain fixed voltage, such as that obtained from a battery, for example, but which depends equally upon the voltage of the alternating-current supply.

Satisfactory results have been obtained in the case of the Italian State Railways substations with a differential relay whose action depends on the difference between the direct-current bus-bar voltage and the r.m.s. voltage of the alternating-current bus-bars. Then if there exists a surplus of energy available throughout that part of the traction system fed by the substation, the direct-current bus-bar voltage will become the preponderating factor and the relay will function so as to initiate the operating sequence appropriate to regenerative working, i.e. inversion of direct to alternating current at the substation. On the other hand, if there is a demand for energy on the part of the traction system, the alternating-current bus-bar voltage will exert a preponderating influence so that the relay will function so as to initiate the reverse sequence of operations, corresponding to normal working, i.e. conversion of alternating to direct current at the substation.

The foregoing system of automatic control of a rectifier substation to achieve regenerative working as and when required has the undoubted advantage that only one rectifier unit is necessary. As far as the author has been able to ascertain the facts it would appear, however, that this system has not met with unqualified success, due to the difficulty in repeatedly controlling the high-speed circuit-breaker, reversing contactors, and grid-excitation equipment from a single and necessarily delicate relay, and with the requisite speed, precision and reliability. The tendency recently has been towards making use of the conventional but more expensive arrangement of two independent conversion units, one connected permanently as a rectifier and the other as an invertor.

The rectifier unit need not necessarily be equipped with grid-control, although this is preferable from the point of view of interchangeability; the invertor unit naturally depends upon grid-control for its operation. The arrangement is shown diagrammatically in Fig. 122, in which *A* and *B* represent the convertor units having secondary windings fed from a common primary *E*.* The direct-current impulse distributors *C* and *D* are driven by a common synchronous motor *F*, supplied from the e.h.t. bus-bars through the auxiliary transformer *G*. In the case of a 3 000-volt traction system, for example, the two grid-excitation equipments are adjusted so that the rectifier unit (*A*) has an output pressure of 3 000 volts at full load, and the invertor unit (*B*) has an input pressure of, say, 3 300 volts.

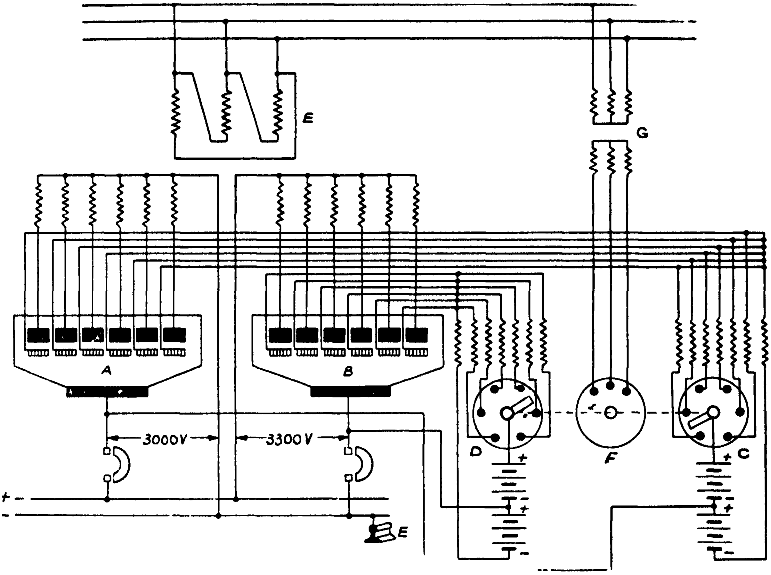

FIG. 122. FUNDAMENTAL CIRCUIT ARRANGEMENT OF COMBINED RECTIFIER AND INVERTOR UNIT
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* As only one convertor unit can operate at a time the kVA rating of this primary winding is that corresponding to full load on *one* secondary winding only: so that in the case of double three-phase operation of the twin unit the mean kVA rating of the transformer as a whole would be 1·65 times the kW output of either convertor unit at full load, i.e. 22 per cent more than in the case of a normal rectifier unit.

Under normal operating conditions the rectifier unit supplies energy to the traction system. As the demand for energy falls, the system voltage rises until eventually it reaches the no-load value of the output voltage of the rectifier unit, which then ceases to supply the system. As soon as a surplus of energy is available, the system voltage tends to rise above this value—which is also the input voltage of the invertor unit (3 300 volts)—and the invertor unit automatically commences to take current from the traction system and, in so doing, to return the surplus energy to the e.h.t. supply system. As the invertor unit operates at fixed voltage the current it takes from the traction system is determined by the amount by which the system voltage exceeds the input voltage of the invertor, which is in turn determined by the amount of surplus energy available. A balance between energy available at the direct-current bus-bars and energy returned to the alternating-current bus-bars is thus automatically maintained, so that stability of the invertor during periods of regeneration is assured. The reversal of energy flow takes place at zero value of the direct current and is a continuous process, two facts which constitute a further important advantage of this system of regenerative working over that making use of a reversible convertor unit.

Fig. 123 illustrates a typical lay-out of a 2 000 kW sub-station containing a combined rectifier and invertor unit for supplying a 3 000-volt traction system. The alternating-current supply is assumed to be three-phase at 88 000 volts and 50 cycles. By comparison with Fig. 124 it is seen that the floor space occupied is less than one-quarter of that taken up by a motor-generator substation of the same output. The overall efficiency of the rectifier equipment at full load is in the neighbourhood of 97 per cent, compared with about 90 per cent, which is as much as can be expected from such a motor-generator set together with its transformer. At lower loads the advantage in favour of the static convertor sub-station is still more marked. For example, at half load the overall efficiency of the rectifier equipment will still be the same, whilst that of the motor-generator set will have fallen by nearly 10 per cent. With the converting plant and auxiliary apparatus as shown in Figs. 123 and 124, the saving in capital cost in favour of static converting equipment lies between 8 and 10 per cent. In actuality the balance in favour of the static substation will be greater than this due to the absence of foundations and to the smaller dimensions of the substation building.

The Self-excited Single-phase Invertor. The polyphase inversion of direct to alternating current is characterized, as has

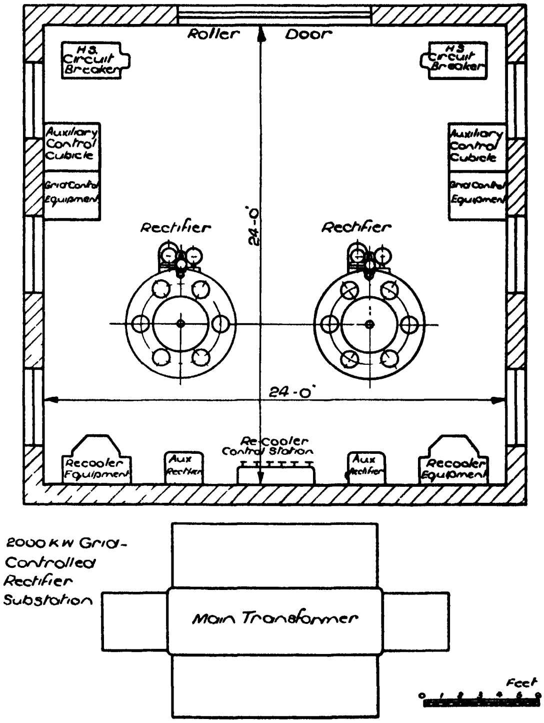

FIG. 123. TYPICAL LAY-OUT OF 2 000-kW RECTIFIER INVERTOR SUBSTATION
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been shown in connection with the invertor applications discussed in the preceding sections of this chapter, by the necessity for an alternating-current supply of constant voltage and fixed frequency. The reason for this is that the several alternating voltages of the polyphase system provide the means for *phase commutation* of the current arc; whilst the periodicity of the alternating-current system determines the cyclical frequency of the commutating process. In other words, the polyphase invertor functions in much the same way as the polyphase rectifier, and its operating characteristics too are not much different. But the process of inversion differs fundamentally from the corresponding process of rectification in that it is not self-maintained. The reason for this essential distinction is not far to seek. In the case of the rectifier the commutation of the arc from anode to anode takes place naturally; in the case of the invertor, on the other hand, arc commutation is forcibly initiated by appropriate excitation of the control grids. The commutating voltage is in both cases, however, a natural agency, characteristic of the circuit; that is, of the combination of electrical apparatus necessary for both voltage transformation and current conversion.

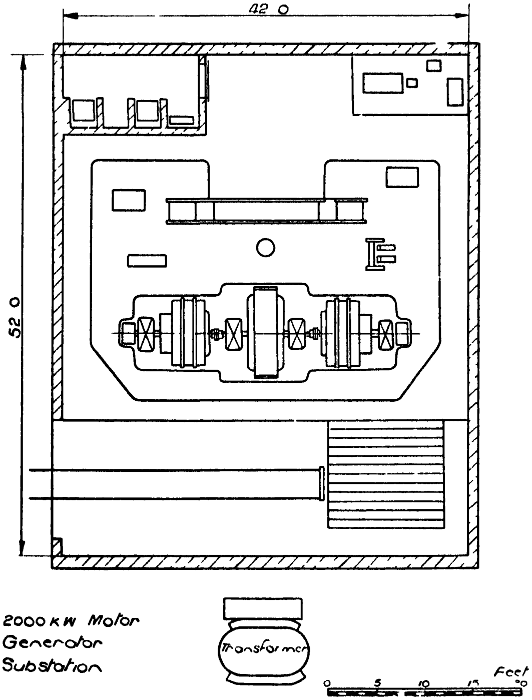

FIG. 124. LAY-OUT OF 2 000-kW MOTOR-GENERATOR SUBSTATION
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Now it is important to remember that, inasmuch as arc commutation is purely a circuit phenomenon, the commutating function may be assigned to several types of circuit. Actually there are only five principal ways in which circuits can be employed to effect arc commutation in an invertor. These may be listed conveniently in accordance with the commutating processes which are characteristic of the different circuits, and are as follows.

1. Phase commutation.
2. Series-condenser commutation.
3. Parallel-condenser commutation.
4. Harmonic commutation.
5. Frequency commutation.

The first of these has been dealt with at some length in this chapter, as already mentioned. The second method is particularly suited to three-electrode tubes of the *thyratron* type and has been fully described by Sabbah in the *General Electric Review*.* The third of these methods is of considerable importance, as it is both simple and stable in operation and is applicable to industrial practice. The fourth system may be looked upon as a modification of the first, as it makes use of some harmonic of the fundamental frequency to effect commutation, and its development is due to Willis.† Of the last method, viz. frequency commutation, practically nothing has as yet been published.‡

The condenser methods of commutation have the advantage that they give rise to a type of mercury-arc invertor which is self-maintained, and whose operation is analogous to the oscillating thermionic valve encountered in broadcasting and radio-telegraphy. As its name implies, parallel-condenser commutation employs a capacitance connected across two or more arc-discharge paths in parallel with each other, the periodic charging and discharging of the capacitance being instrumental in commutating the arc from one discharge path to the next. The self-maintaining feature is obtained by electromagnetic coupling of the grid and anode circuits, so that the commutating frequency is determined by the electrical constants of the complete invertor circuit. The limiting upper frequency is determined by the time required for complete deionization of the arc discharge path to take place, and lies between 2 000 and 5 000 cycles per second. The lower frequency limit for stable operation appears to be of the order of 5 cycles per second, and is fixed mainly by the prohibitive size and cost of the commutating condenser at very low frequencies.

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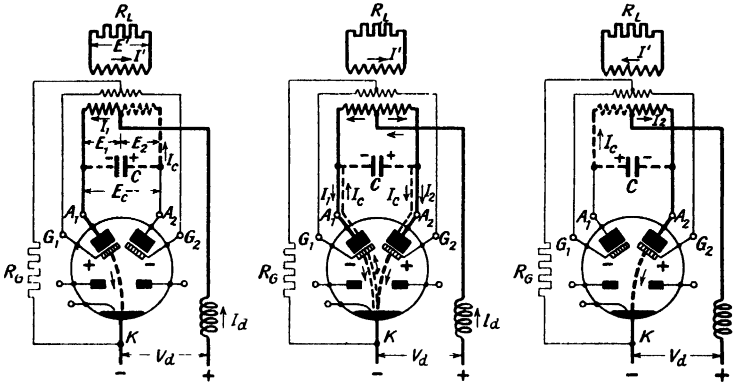
* *Vide General Electric Review*, 1931, Vol, 34, pp. 288, 580, and 738.

† *Vide* C. H. Willis: "Applications of Harmonic Commutation for Thyratron Rectifiers and Invertors," Paper No. 33–18 presented at the Winter Convention of the Am.I.E.E. in January, 1933.

‡ An article by Dr. Willis on the "Thyratron Commutator Motor" is due to appear in the *General Electric Review*, but at the time of going to Press this is not yet published. This particular type of alternating-current motor employs frequency commutation at starting and during low-speed operation.

The only "parallel" type of invertor which has so far reached the commercial stage of development is the self-excited single-phase invertor illustrated diagrammatically in Fig. 125. The invertor is supplied with direct current through a smoothing reactor, and the commutating condenser C is connected in parallel with the primary winding of the output transformer, that is, between the two anodes A_1 and A_2 of the single-phase current convertor. The grids G_1 and G_2 are energized from a tertiary winding on this transformer, the neutral point of which is connected to the cathode *via* a current-limiting resistance R_G. The operation of such an invertor when loaded by a pure resistance R_L may be explained as follows.



(a) Conducting Period t_2-t_3 (b) Commutating Period t_3-t_4 (c) Conducting Period t_4-t_1

FIG. 125. OPERATION OF SELF-EXCITED SINGLE-PHASE INVERTOR

Referring to Fig. 125 (*a*), and considering the instant t_1 in which grid G_1 has just become positive, the direct current I_d will be carried by anode A_1 as shown by diagram (*d*) of Fig. 126.

At the same time the condenser immediately commences to charge up, the charging current flowing through the other half of the transformer primary. After time t_1, therefore, $I_2 = I_c$ and $I_1 = (I_{A1} - I_c)$; this is shown by diagrams (*b*), (*d*) and (*f*) of Fig. 126. In other words the anode current I_{A1} has two components, viz. the corresponding transformer primary current I_1, and the charging current I_c. Shortly afterwards, at time t_2, the voltage of anode A_2 becomes positive, so that G_2 must be kept at a negative potential. At this instant also the transformer primary (E_1, E_2) and secondary (E') voltages are zero, as may be seen from diagrams (*e*) and (*g*) of Fig. 126. Comparing these with diagram (*d*) it is seen that this condition does not exist until some time after the anode current has started, thus showing that *the latter leads the induced voltages.* This condition is fundamental to the operation of this type of invertor, and it is a principal function of the commutating condenser C to provide this phase relation. An important feature of such an invertor is that the condenser can be dispensed with entirely if the power factor of the load on the transformer secondary is leading to a sufficient extent, as under these circumstances the load provides the necessary phase relation for stable invertor operation.

Some time after the instant t_2, the condenser becomes fully charged. The condenser voltage E_c then reaches its maximum value—approximately twice that of the direct-current supply voltage V_d—whilst the condenser current I_c falls to zero. This is shown by diagrams (*a*) and (*b*) of Fig. 126. At time t_3 grid G_2 becomes positive. The anode voltage E_{A2} collapses to the arc drop value ε, and the discharge path $A_2 - K$ is thereby made conducting. As indicated in Fig. 125 (*b*) the condenser immediately discharges through the short-circuit path $A_2 - K - A_1$, which is of exceedingly low impedance. The condenser voltage E_c is in opposition to the anode current I_{A1}, so that the voltage of anode A_1 becomes negative immediately the condenser starts to discharge, as may be seen from diagram (*c*) of Fig. 126. As the result, the current carried by anode A_1 falls to zero, i.e. the arc is extinguished, and the impedance of the discharge path $A_1 - K$ immediately resumes the high value appropriate to the non-conducting state. The anode voltage E_{A1} remains negative until time t_4 is reached, when it passes through its zero value once more. Hence the grid G_1 must be made negative again during the interval $t_3 - t_4$, the duration

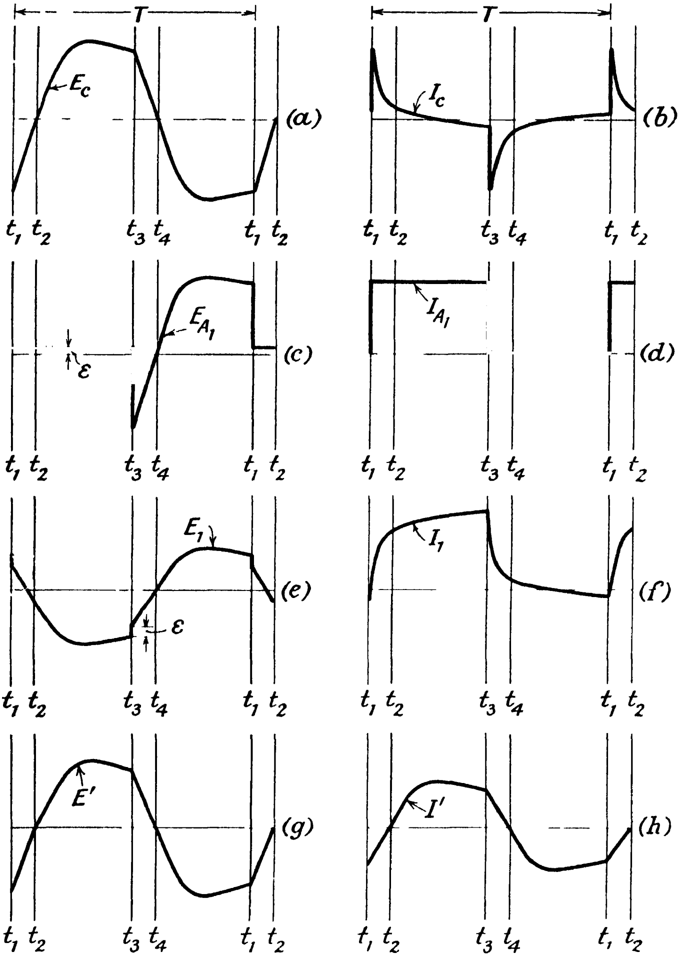


FIG. 126. VOLTAGE AND CURRENT WAVE FORMS OF SINGLE-PHASE INVERTOR

of which must be such that complete deionization of the discharge path $A_1 - K$ can take place. If this condition is not fulfilled the grid G_1 cannot regain control, and the arc will be re-established at anode A_1 the moment E_{A1} becomes positive at time t_4. *It is a further principal function of the commutating condenser C to provide this interval of time for deionizing of* *the arc path.* This deionizing period is determined by the capacitance value of the commutating condenser, and is approximately proportional to it. Under normal conditions of operation the *deionizing time* of such a mercury-arc invertor is of the order of 100 micro-seconds.

As soon as I_{A1} has fallen to zero (at time t_3) the condenser commences to charge up with reversed polarity, the condenser current I_c diminishing in the process as may be seen from diagram (*b*) of Fig. 126. This charging current now flows through that half of the transformer primary connected to anode A_1, whilst the other half carries the remaining component of the anode current I_{A2}. As shown in Fig. 125 (*c*), a condition is thus reached which is the same as that illustrated by Fig. 125 (*a*). This condition is maintained until the end of the cycle, at the instant t_1, when the condenser is again short-circuited by making grid G_1 positive once more.

The foregoing explanation of the operating sequence during the inversion of direct current to single-phase alternating current takes no account of the finite time required for commutation. The commutating condenser obviously cannot discharge instantaneously, as indicated in Fig. 126; neither can the current arc be transferred instantaneously from the one anode to the other. In practice the time required for complete commutation is determined by the latter consideration. As in the case of the rectifier, we meet with a definite *angle of overlap* in the invertor; and it is readily seen that stable invertor operation can only be obtained if the intervals t_1-t_2, t_3-t_4 are each greater than the sum of the deionizing and overlap periods. And as the angle of overlap increases with load it is therefore essential that the capacitance of the commutating condenser is large enough to ensure satisfactory commutation at maximum load.

The Dual-conversion System of Static Frequency Changing. An important type of service for which the mercury-arc current convertor has been successfully employed in these last few years is the changing of frequency required on the Continent, due to the supply of single-phase alternating-current railway systems at $16\frac{2}{3}$ cycles per second, and often in demand in this country also, due to the recent standardization of a frequency of 50 cycles per second. In general, where it is necessary to interconnect two alternating-current networks operating at different frequencies, an elastic link is to be preferred. A rigid (i.e. synchronous) link should only be resorted to where the two networks have the same frequency—in which case a transformer is the obvious interconnecting unit to be employed. The elastic method of interconnection is, however, of necessity very costly, on account of the large amount of auxiliary plant and control gear associated with asynchronous-synchronous frequency changers, so that the tendency has been, on the Continent at any rate, to make use of synchronous motor-alternator sets, providing a rigid coupling between the two alternating-current systems. But the increasing size and complexity of modern high-tension power networks, bringing in their train a host of perplexing problems connected with stability, voltage compensation and the interchange of reactive power, are making it almost essential for any interconnecting link to be completely elastic, that is, asynchronous in character.

The introduction of the mercury-arc current convertor to modern electrical engineering practice has brought with it the possibility of applying such plant to the practical and economic solution of this frequency-changing problem. One solution in particular which will immediately be perceived, especially if one bears in mind the possible use of high-tension direct-current transmission,* is a static frequency convertor comprising a rectifier supplying direct current to an invertor. By the provision of grid control it is then possible to interchange the functions of rectification and conversion in accordance with the direction in which the flow of power is required.

Such a *dual-conversion* system of static frequency-changing is illustrated diagrammatically in Fig. 127, as applied to the supply of a single-phase $16\frac{2}{3}$-cycle traction network from a three-phase 50-cycle power system. In this case it is assumed that the lower-frequency system is devoid of synchronous machinery, and that the flow of power is in the one direction only. Under these circumstances the polyphase rectifier connected to the 50-cycle supply will be designed to operate at maximum efficiency, so that its direct-current output voltage will be high—of the order of 1 000 or 2 000 volts. The output current is fed to the single-phase invertor through a large smoothing reactor so as to reduce the harmonic ripple to a minimum value. Like the induction generator, the mercury-arc invertor requires a synchronous machine to determine the frequency of the alternating-current output and to supply the reactive power requirements of the load. A synchronous condenser connected to the output terminals of the single-phase invertor thus forms an integral part of this type of static frequency-changing unit. In addition, the machine supplies the magnetizing current of the invertor transformer as well as the harmonics inevitably associated with static current-converting plant. Considering the frequency convertor from the point of view of energy transfer, the smoothing reactor and synchronous condenser each contribute to the storage of the instantaneous difference between the constant power input from the three-phase supply and the pulsating single-phase power output to the traction system.

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* *Cf.* H. Rissik: "Some Aspects of the Electrical Transmission of Power by Means of Direct Current at Very High Voltages," *Journal I.E.E.*, 1934, Vol. 75, p. 1.

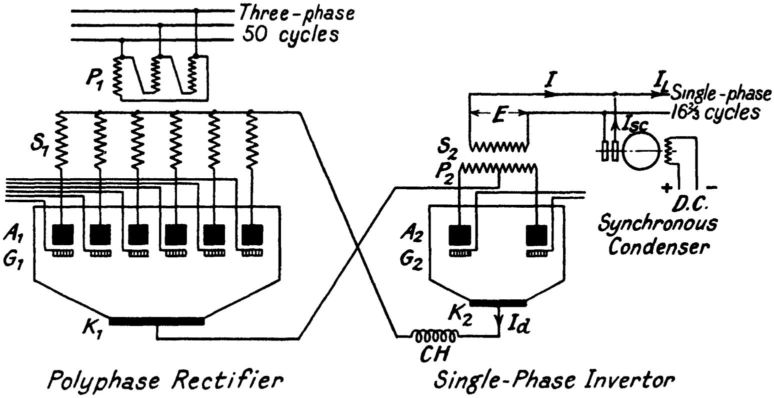

FIG. 127. DUAL-CONVERSION STATIC FREQUENCY CHANGER

In the arrangement of Fig. 127, where the invertor unit is connected to a synchronous machine, the transfer of the current arc in the invertor from one anode to the other is effected in the normal way by phase commutation—a process which has been described earlier in the present chapter in connection with polyphase invertors. The actual commutating process in this single-phase case is illustrated by Fig. 128. As usual, commutation of the arc can only take place when the idle anode is at a higher potential than the working anode. Consequently the grid of the former anode must be made positive some time before the anode voltage passes through zero, the angle of ignition advance being indicated by α in the diagram.

Moreover, due to the inductive reactance of the alternating-current system supplied by the invertor, commutation is not effected instantly, but requires a certain time for its completion. The commutating period is defined by the angle of overlap u and is a function of the load. In order that the grid of the previously working anode may regain control after the arc transfer has been completed, a further time interval must be available between the end of the overlap period u and the zero passage of the anode voltage. This time interval is equal to the time required for deionization of the arc-discharge path, and is indicated by the angle δ. *Under all conditions of invertor loading, therefore, the relation* $\alpha > u + \delta$ *must always obtain, as otherwise the invertor will become unstable.*

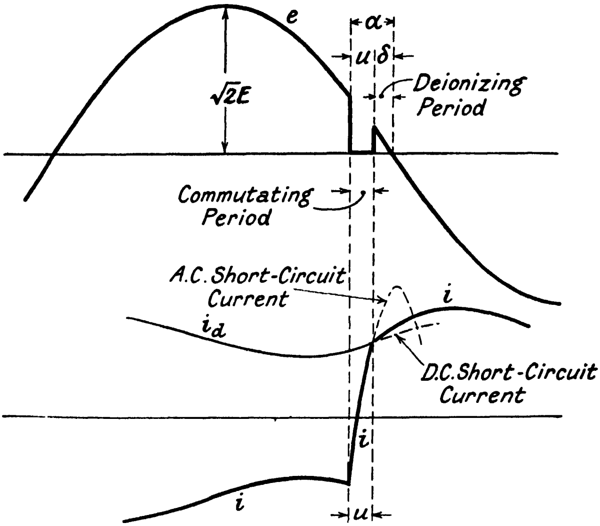

Fig. 128. Output Voltage and Current during Commutation

The anode-current growth is shown in the lower diagram of Fig. 128. Initially the anode current follows the short-circuit current of the alternating-current system. As soon as it reaches a value equal to the short-circuit current of the direct-current supply system, it follows the normal course dictated by the impedance of the invertor circuit. It is seen that current and voltage are displaced in phase by the angle $(\alpha - u)$, so that the displacement factor* is equal to cos $(\alpha - u)$. Furthermore, the current leads the induced voltage so that the displacement factor of the invertor is *leading*—a condition already observed in connection with the self-excited type of single-phase invertor. The reactive power consumption of the invertor is, of course, proportional to tan $(\alpha - u)$, so that it is generally desirable to keep the angle of ignition advance as small as possible. At the same time it must be large enough to ensure satisfactory commutation even under extreme overload conditions, when the angle of overlap may be considerable.

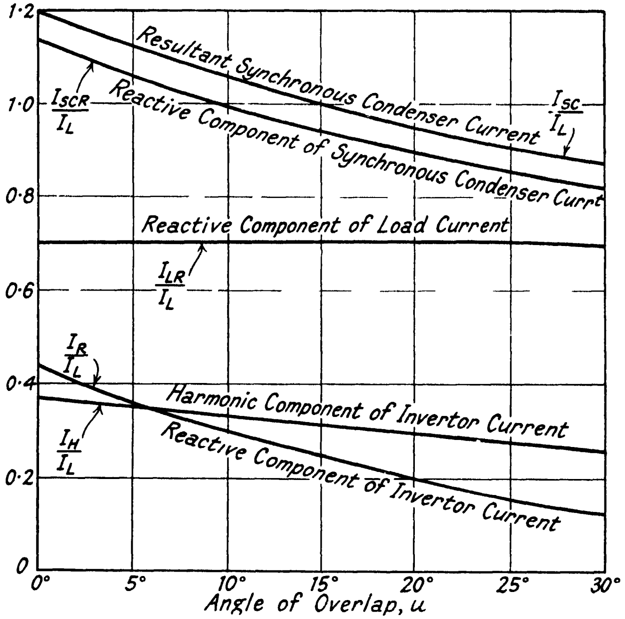

FIG. 129. WATTLESS CURRENT SUPPLY BY THE SYNCHRONOUS CONDENSER

($\cos\phi_L = 0{\cdot}7$; $\alpha - 30°$)

The single-phase system may be regarded as an alternating-current load on the invertor, and expressed by the load current I_L. The load will normally be inductive, so that this load current has two components: the power component I_{LP} and the reactive component I_{LR}. The former only is supplied by the invertor, as the direct-current input cannot possibly contain a quadrature component. The reactive component of the load current must therefore be supplied by the synchronous condenser, which has already had to supply the reactive power

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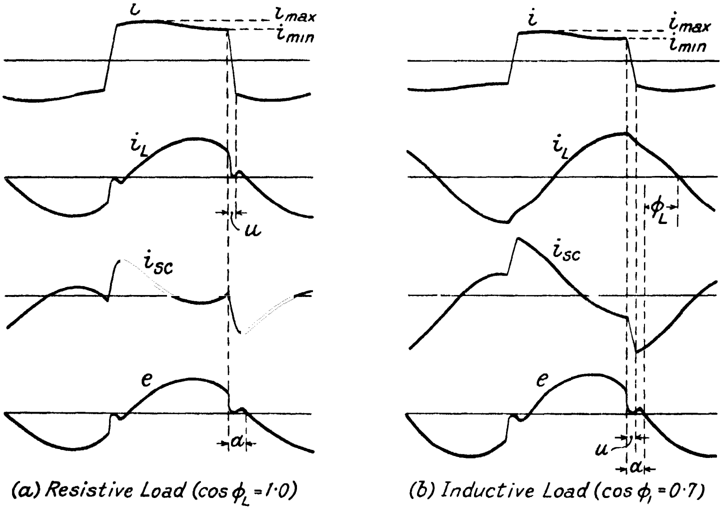
* That is, the quantity referred to as "power factor" in the case of normal sinusoidal alternating-current circuits. In the case of current convertors and like apparatus, which introduce harmonic distortion, power factor does not have the same meaning. This question is dealt with in Chapter XIV.



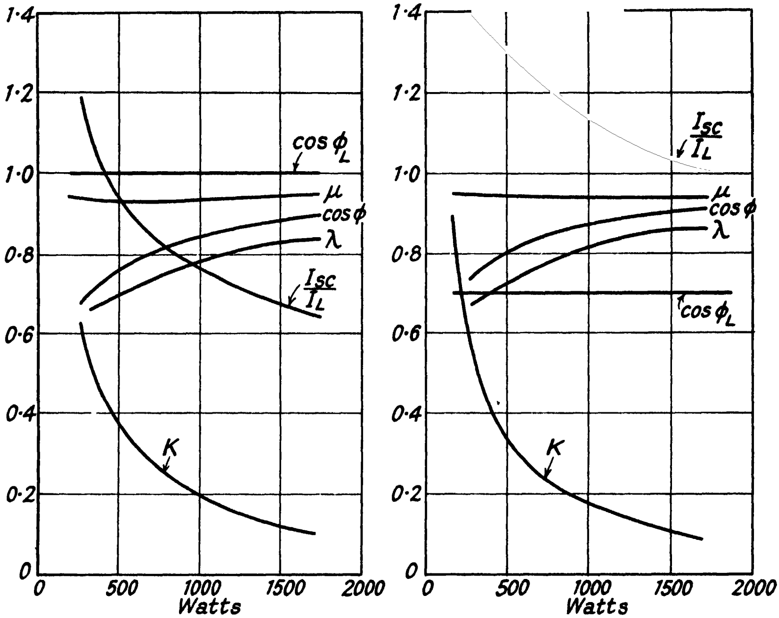
(a) Resistive Load ($\cos\phi_L = 1{\cdot}0$)   (b) Inductive Load ($\cos\phi_l = 0{\cdot}7$)

FIG. 130. CURRENT AND VOLTAGE WAVE-FORM OF A 1·5-KW STATIC FREQUENCY CHANGER

requirements of the invertor as determined by the angles α and u, as well as the harmonics necessary for maintaining a sinusoidal output. Denoting the power and reactive components of the invertor current by I_P and I_R respectively, and the harmonic component by I_H, we thus have: $I_{LP} = I_P$; $I_{SC} = \sqrt{[(I_R + I_{LR})^2 + I_H{}^2]}$, where I_{SC} is the total current supplied by the synchronous condenser. The variation of these several current components with load, as expressed by the angle of overlap u, is shown by the curves of Fig. 129. These refer to an angle of ignition advance of $\alpha = 30°$, and to an inductive load of $\cos\phi_L = 0{\cdot}7$, and it is assumed that the direct-current input is maintained constant by means of an infinitely large smoothing reactor.

The results of tests carried out by Reinhardt on a 1 500-watt rectifier-invertor unit are shown in Figs. 130 and 131. Figs.

130 (*a*) and 131 (*a*) relate to a resistance load on the single-phase side; whilst in the case of Figs. 130 (*b*) and 131 (*b*) the invertor loading was inductive with $\cos \phi_L = 0{\cdot}7$. The fluctuation in value of the invertor current, due to the finite value of the smoothing reactor, is clearly shown in the upper oscillograms. The degree of fluctuation is conveniently expressed by the *undulation factor* $K = (i_{max} - i_{min})/(i_{max} + i_{min})$, which gives the ratio of the peak harmonic ripple to the mean current. The magnitude of the synchronous condenser current I_{sc} depends not only upon the angle of overlap u (assuming α to be kept constant), but also upon the value of K. As may be seen from the oscillograms, the effect of the undulation in the invertor current is to shift the centre of gravity of the half-wave towards the left, thereby increasing the phase displacement between the fundamental component of the invertor current and the output voltage. The additional reactive power consumption occasioned by this displacement is reflected in



(a) Resistive Load ($\cos\phi_L$=1·0) (b) Inductive Load ($\cos\phi_L$=0·7)

FIG 131. OPERATING CHARACTERISTICS OF THE 1·5-KW STATIC FREQUENCY CHANGER

the drooping of the displacement factor curve, $\cos \phi$ in Fig. 131, at the lower loads. The displacement factor falls off more rapidly than one would expect from a consideration of the angle of overlap alone. Fig. 131 also shows the variation of the overall power factor λ, and the distortion factor μ with the load on the invertor. Furthermore, it is seen that the wattless current I_{sc} supplied by the synchronous condenser increases very rapidly with falling load. At full load the kVA output of this machine is only two-thirds of the kW output of the invertor, whilst at one-quarter load the wattless power output of the synchronous condenser already exceeds the active power output of the invertor.

According to Reinhardt, who has carried out further full-scale experiments with a 500 kW dual-conversion frequency convertor, the pronounced technical advantages of this system of static frequency changing, viz. complete elasticity of the link between the three-phase and single-phase networks, simplicity of power control, and high power factor on the three-phase side, are associated with the drawback of high initial cost due to the inclusion of the synchronous condenser. In the case of a single-phase load having a power factor of $\cos \phi_L = 0{\cdot}7$, the capital cost of such a static frequency-changing unit is likely to exceed that of an asynchronous motor-generator set by as much as 15 per cent. A reduction in cost can only be brought about by reducing the size of the synchronous condenser, which, in turn, is only possible if means be available for commutating the invertor current, *after* the induced voltage has passed through zero. To achieve this end it is necessary either to dispense with phase commutation, and to employ instead the parallel-condenser method of commutation discussed in the preceding section, or to employ new methods of grid-control actually to *extinguish* the current arc at the appropriate instant in the voltage cycle. The former alternative is more immediately practicable, but is likely to prove expensive; the latter has already found some measure of success in the screened-grid controlled rectifier developed by Kobel.*

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(2) R. Feinberg: *Archiv für Elektrotechnik*, 1932, Vol. 26, p. 200.
(3) G. Reinhardt: *Elektrotechnik und Maschinenbau*, 1934, Vol. 52, p. 261.

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* *Vide* Chapter XIII.

CHAPTER XII

THE MERCURY-ARC CYCLOCONVERTOR

In the case of the dual-conversion system of static frequency changing discussed in the preceding chapter, the power factor of the load imposed by the frequency-convertor on the three-phase supply is obviously identical with that of a normal rectifier unit of the same output. The 50-cycle system in no way contributes towards the supply of reactive power to the lower-frequency system, and any demand for wattless (magnetizing) current on the part of the latter must therefore be met either by existing synchronous plant or else by a machine specifically provided for this purpose—such as an alternator, synchronous motor, or synchronous condenser. The reason for this, of course, is the fact that the direct-current circuit constituting the power link between the rectifier and invertor elements of the static frequency-changing unit operates at zero frequency, and is consequently incapable of carrying a quadrature component of current; that is to say, it cannot transmit reactive power.

Static frequency-changing arrangements which permit of the interchange of wattless power in addition to useful power are characterized by the absence of the direct-current link between the current-converting elements of the composite unit. In other words, the two alternating-current systems are directly coupled as regards the transference of both active and reactive power. Furthermore, such frequency-convertors possess no inherent means of energy storage, so that the power pulsation in the single-phase output is fully transmitted to the three-phase side, where it manifests itself as an asymmetry in the loading of the individual phases.

Fundamental Considerations. Direct frequency-changing systems of this class employ two similar polyphase current convertors connected together in accordance with a common fundamental principle, namely, that of artificially building up an alternating voltage wave of lower frequency from successive voltage waves of a higher-frequency polyphase system. The author has given the term *cycloconversion* to this novel process of static voltage generation, and has accordingly designated static frequency-convertors of this type as *cycloconvertors.* Fig. 132 illustrates the fundamental circuit arrangement typical of all cycloconversion systems for changing three-phase alternating current at a given frequency into single-phase alternating current at a lower frequency.

The three-phase system supplies two polyphase rectifiers

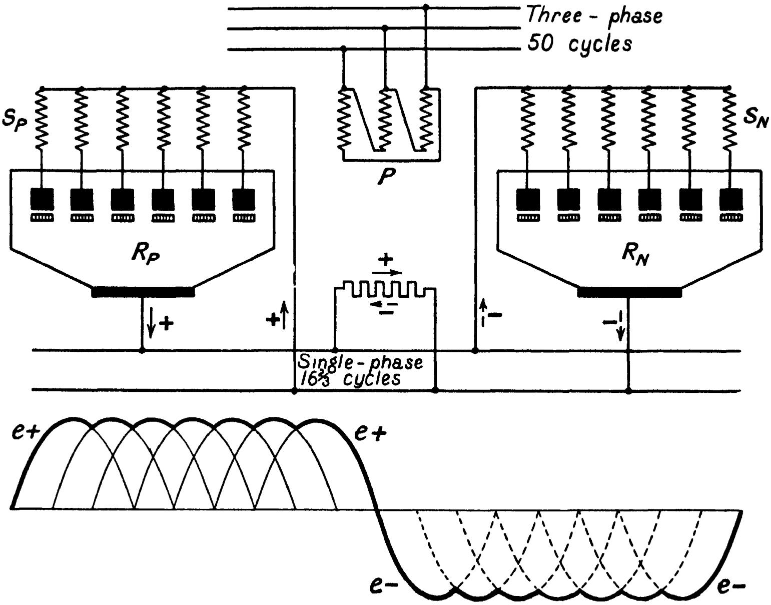

FIG. 132. CONNECTIONS AND OUTPUT VOLTAGE OF SYNCHRONOUS CYCLOCONVERTOR

through the medium of, say, a 50-cycle transformer provided with a primary winding *P* and two secondary windings S_P and S_N. The rectifiers R_P and R_N are connected in opposition, i.e. "back-to-back," on the output side, and the single-phase supply is taken from the two cathodes. The rectifiers are controlled in such a manner* that they come into operation alternately. For example, in the case of a 3 : 1 frequency ratio, as illustrated in Fig. 132, one rectifier, R_P, carries current during one and a half cycles at supply frequency, and becomes idle during a further one and a half cycles in which the other rectifier, R_N, carries current. The positive direction of current-flow in the single-phase load circuit is indicated by the solid arrow, the negative direction of current-flow by the broken arrows. As shown in the lower diagram of the illustration, the first rectifier then generates a positive half-wave of voltage at the lower frequency, whilst the other rectifier generates the corresponding negative half-wave. It is seen that the single-phase output voltage has a more or less rectangular wave-form, which is a disadvantage that detracts from the general usefulness of this type of cycloconvertor.

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* In practice grid control is employed for this purpose. But early patent specifications, published before the grid-controlled rectifier became a *fait accompli,* illustrate and describe the use of drum-type controllers connected in the anode circuits for bringing the rectifiers into and out of operation.

For this reason efforts have in recent years been directed to improving the wave-form and, in particular, to obtaining a sinusoidal output voltage, having a periodicity of 16⅔ cycles per second, from a 50-cycle supply. Two principal solutions of this particular problem have been reached, both of them being based on what has come to be known as the *envelope** method of cycloconversion. One of these solutions provides a frequency change which is completely synchronous, as is that shown diagrammatically in Fig. 132. In the case of the other, the change of frequency is asynchronous in character, so that the cycloconvertor constitutes a flexible link between the three-phase and single-phase systems. Both types of envelope cycloconvertor, however, are characterized by the fact that the frequencies of the two alternating-current systems are of necessity fixed in the ratio of 3 to 1.

The conditions of current flow and the voltage wave-forms on the three-phase and single-phase sides of a cycloconvertor of the simple type shown in Fig. 132 are depicted in Fig. 133. The blocks of current flowing in the anode circuits of the two six-phase rectifiers are indicated by 1, 2, 3 . . . 6. These anode currents, of course, flow in succession and appear in the single-phase output circuit as the sinusoidal current i. The corresponding blocks of current flowing in the three phases of the transformer primary are indicated by the shaded areas 1, 2, 3 . . . 6. It is seen that they are not symmetrically distributed with respect to the three phases. One phase current (i_2') has, in fact, an r.m.s. value approximately 7 per cent greater than that of the remaining two (i_1' and i_3').

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* The reason for this rather peculiar term will become apparent later on when considering the mode of generating the lower-frequency voltage wave.

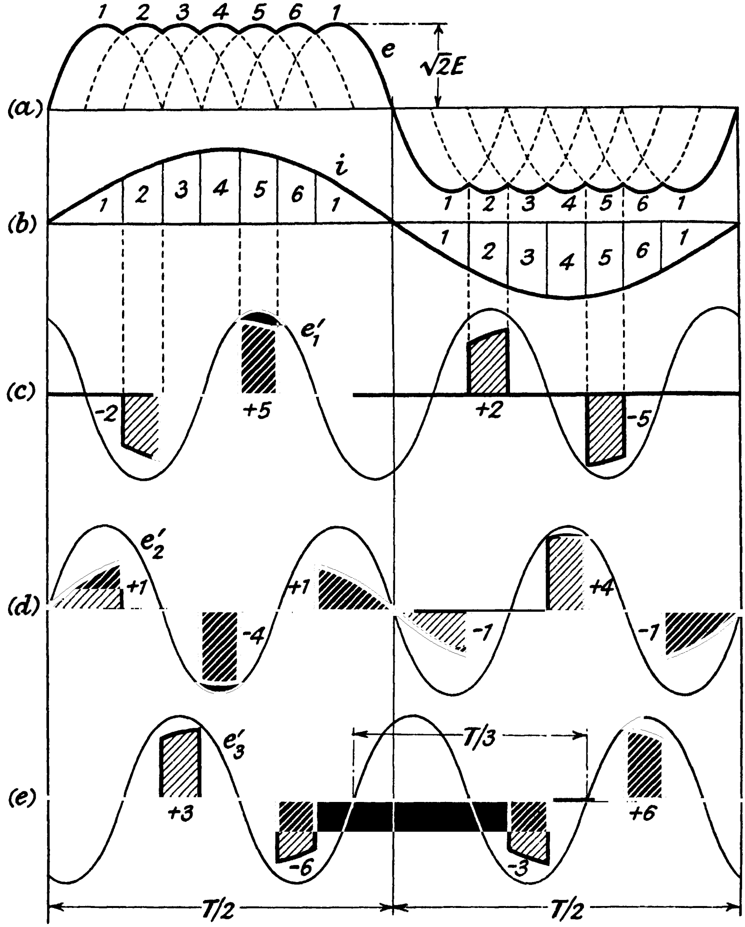

FIG. 133. OUTPUT AND INPUT VOLTAGE AND CURRENT WAVE-FORMS

(a) = Single-phase output voltage e (c), (d), (e) = Three-phase input voltages
(b) = Single-phase output current i e'_1, e'_2, e'_3 and currents i'_1, i'_2, i'_3

In the case of the six-phase cycloconvertor unit of Figs. 132 and 133, the ratio between the r.m.s. and peak values of the single-phase voltage e is found to be 0·85. Assuming a transformer turns-ratio of 1 : 1, then the peak values of the single-phase and three-phase voltages are equal; so that we have $E = 1{\cdot}2E'$. Moreover, we have $I^2 = (I_1')^2 + (I_2')^2 + (I_3')^2$. Assuming all three primary currents to have the same r.m.s.

value I', we may, therefore, write $I = (\sqrt{3})I'$. Now the kW output (single-phase) of the cycloconvertor at unity power factor is EI, whilst the corresponding kVA input (three-phase) is $3E'I'$. The ratio of these two quantities—the *utility factor* of the cycloconvertor—is thus $EI/3E'I' = \frac{1}{3} \times 1{\cdot}2 \times \sqrt{3} = 0{\cdot}693$ and is, in fact, identical with the distortion factor of the primary winding. If the latter is delta-connected, the line currents will have an r.m.s. value equal to $(\sqrt{2})I'$, due to the absence of the third harmonic.* The line kVA is thus

$$(\sqrt{3}) \,.\, E' \,.\, (\sqrt{2})I = (\sqrt{6})E'I'$$

The true *distortion factor* of the cycloconvertor is consequently

$$\mu = \frac{EI}{(\sqrt{6})E'I'} = \frac{1}{\sqrt{6}} \times 1{\cdot}2 \times \sqrt{3} = 0{\cdot}85$$

In the case of a normal six-phase rectifier, the distortion factor is $0{\cdot}955$; so that a cycloconvertor increases the line-current distortion by some 12 per cent as compared with a rectifier of the same kW output. These relations naturally hold good only where the kW and kVA outputs on the single-phase side are numerically the same, that is, if the power factor of the single-phase load is equal to unity. If reactive power is transmitted from the three-phase system to the single-phase system in addition to active power, then, neglecting the magnetizing kVA of the transformer, the kVAR input must equal the kVAR output. And as reactive power is primarily a function of the frequency of the alternating current and is, in point of fact, inversely proportional to the frequency, we obtain the simple relation: $\tan\phi' = \frac{1}{3}\tan\phi$, where $\cos\phi'$ is the *displacement factor* on the three-phase side corresponding to a power factor $\cos\phi$ of the single-phase load. This relation may also be expressed as $\cos\phi' = 1/\sqrt{(1 + \frac{1}{9}\tan^2\phi)}$. The *power factor*† of the cycloconvertor is then finally given by $\lambda = \mu\cos\phi' = 0{\cdot}85/\sqrt{(1 + \frac{1}{9}\tan^2\phi)}$.

The Synchronous Envelope Cycloconvertor. The synchronous system of *envelope* cycloconversion is due to Löbl,‡ who seems to have been the first to attempt to improve the wave-form of the single-phase output voltage. With this system the successive phases of the transformer secondary windings are graded with respect to voltage in such a manner that the envelope of the anode voltage waves provides the desired sinusoidal wave-form.* The amplitudes of the successive anode voltages vary as the cosine of the angle between the midpoints of the anode and output voltage waves. Thus in the case of the six-phase system illustrated in Fig. 134, phase 1 has a voltage 33 per cent, phases 2 and 6 have voltages 73 per cent, and phases 3 and 5 have voltages 93 per cent of that of phase 4.

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* *Cf.* Chapter V: Six-phase Rectification.

† *Vide* Chapter XIV.

‡ *Vide* O. Löbl: "The Löbl-RWE Cycloconvertor as Applied to Single-phase Traction Supply," *Elektrische Bahnen*, 1932, Vol. 8, pp. 65–69.

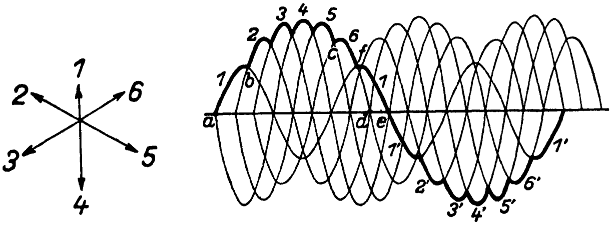

FIG. 134. OUTPUT VOLTAGE OF THE LOBL CYCLOCONVERTOR
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The current wave-forms obtained on the three-phase side are generally similar to those shown in Fig. 133. An analysis of these has been carried out by Feinberg, who has found the following expressions for the active and reactive components of the line current, assuming a transformer ratio of 1 : 1

$$I_P' = 0{\cdot}54 I \cos\phi ; \; I_R' = 0{\cdot}18\, I \sin\phi$$

where cos ϕ is the power factor and sin ϕ the induction factor of the single-phase load. As is to be expected, the above expressions give rise to the general relation

$$\tan\phi' = I_R'/I_P' = \tfrac{1}{3}\tan\phi$$

between the angular phase displacements of current and voltage on the two sides of the cycloconvertor. The distortion factor of the Löbl type of cycloconvertor is somewhat lower than that of the straightforward unit discussed in the preceding section, and is equal to $\mu = 0{\cdot}76$ with unity power factor on the single-phase side. The relation between power factor λ, distortion factor μ, and displacement factor $\cos \phi'$ on the three-phase side, and the single-phase power factor $\cos \phi$ is indicated by the curves of Fig. 135. The variation in the mean kVA rating P_T of the associated transformer with $\cos \phi$, assuming a constant kVA output P, is also shown in the diagram.

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* Hence the term *envelope* cycloconvertor.

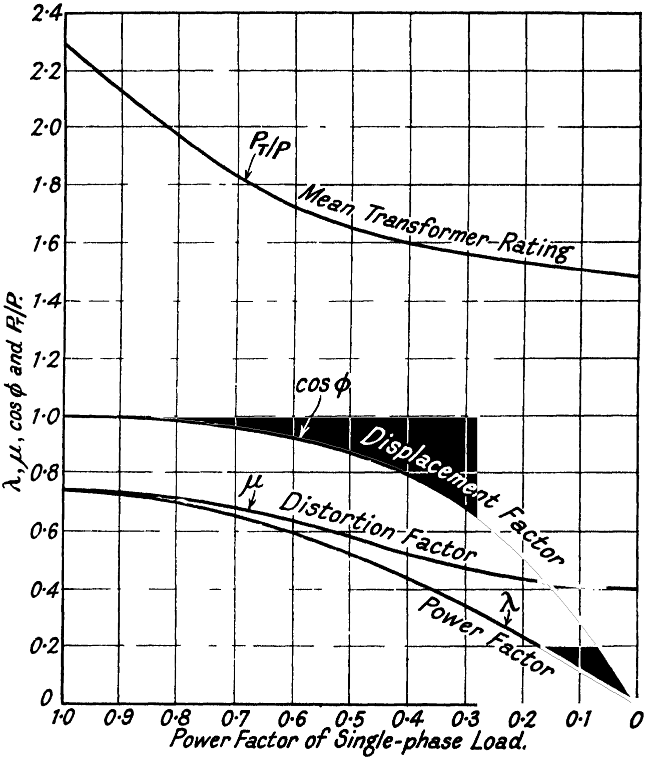


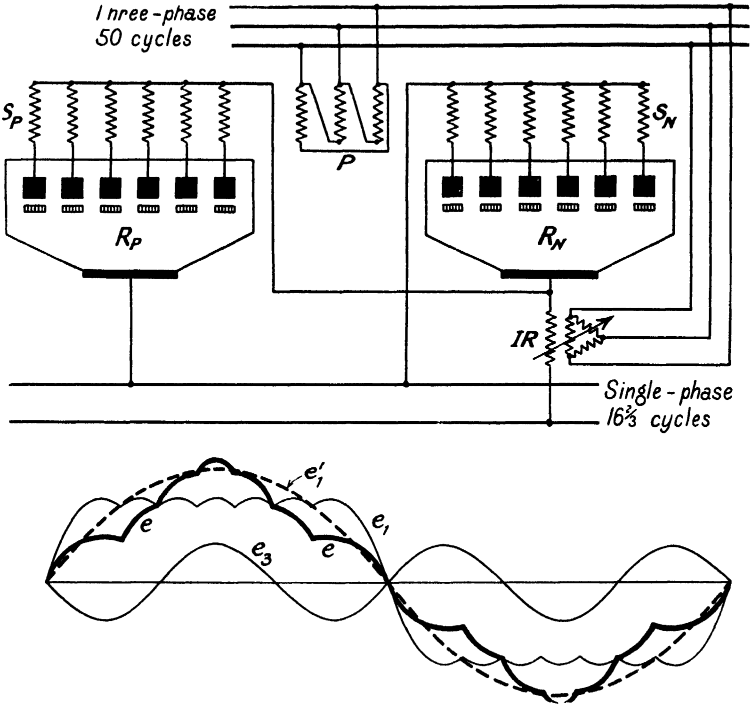
FIG. 135. INPUT POWER RELATIONS OF THE LOBL CYCLOCONVERTOR

Up to the present little information has been published about the performance and general operating characteristics of the Löbl cycloconvertor. It is known, however, that towards the end of 1931 tests were carried out with a medium-sized unit, comprising two 100-kW steel-tank rectifiers, which was employed to supply a type B–B goods locomotive (equipped with two 400 kW motors) loaned by the German State Railways and arranged to run on a 2½-mile single-phase track belonging to the Rheinisch-Westfälische Elektrizitätswerke. The general working of such a cycloconvertor was demonstrated first of all by its ability to supply various kinds of single-phase load, e.g. a resistance dissipating 200 kW, a 120-kVA reactor, and a 160-kW traction motor. The cycloconvertor unit was designed to deal with approximately 100 kVA, at 544 volts and 16⅔ cycles per second, on the single-phase side. The supply was three-phase at 418 volts and 50 cycles per second. These tests indicated that the unit had an overall efficiency of 91 per cent at full load, and that the efficiency remained constant for all values of $\cos\phi$ between zero and unity. The voltage drop between no load and full load amounted to 10 per cent at unity power factor, and 8 per cent at $\cos\phi = 0{\cdot}7$.

The Asynchronous Envelope Cycloconvertor. The outstanding feature of the Löbl cycloconvertor is that it compels a rigid phase relationship between the higher-frequency and lower-frequency alternating-current systems. This inherent rigidity in the frequency-changing process constitutes one of the principal disadvantages of this type of cycloconvertor, notwithstanding that it produces, in a relatively simple manner, a single-phase output voltage which approximates closely to the sinusoidal in wave-form. An improved type of cycloconvertor, which combines the "envelope" method of providing a close approximation to the true sine wave with a means for giving the frequency conversion process an asynchronous character, has been successfully developed by Krämer and is illustrated diagrammatically in Fig. 136.

The trapezoidal output-voltage wave of Fig. 132 is changed to an approximate sine wave by having superposed upon it a 33⅓ per cent negative third-harmonic voltage, i.e. an alternating voltage having a periodicity of $3 \times 16\frac{2}{3} = 50$ cycles per second. This additional voltage is obtained from an induction regulator having a single-phase secondary winding connected in series with one of the rectifier units of the cycloconvertor. The three-phase primary winding of this induction regulator is then fed from the 50-cycle supply. In other words, the Krämer cycloconvertor employs a transformer with symmetrical secondary windings together with an induction regulator connected in the low-frequency circuit and excited from the three-phase supply.

The resulting frequency-change is quite asynchronous in character, as the rotor of the induction regulator is free to rotate and may take up any phase position with respect to the stator. The relative phase position of the voltage added by the regulator, and thus of the resultant single-phase output voltage of the cycloconvertor, is then determined solely by the frequency and phase relationships of the two alternating-current systems. If, for example, the frequency ratio varies slightly from the normal, the rotor of the induction regulator rotates slowly at a speed corresponding to the frequency difference. This is illustrated by Fig. 137, the upper diagrams of which indicate two different phase positions of the induction regulator. In the one case the additional voltage is in phase with the voltage of anode 1, whilst in the other



e_1 = Trapezoidal wave of fundamental frequency (16⅔ cycles)
e_3 Sinusoidal wave of third harmonic frequency (50 cycles)
e = Resultant voltage wave
e' = Fundamental component of resultant voltage wave

FIG. 136. CONNECTIONS AND OUTPUT VOLTAGE OF ASYNCHRONOUS CYCLOCONVERTOR

case it is displaced from this position by 30 electrical degrees. The latter position represents a displacement in phase of the resultant single-phase output voltage of 10 electrical degrees. In the lower diagram the fundamental component of the output voltage is indicated by the dotted curve. The full-line curve is the resultant single-phase voltage, and it is seen that the wave-form compares favourably with that of the Löbl cycloconvertor given in Fig. 134.

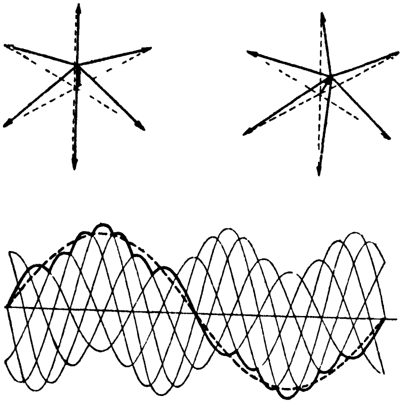


FIG. 137. PHASE-SHIFT OF OUTPUT VOLTAGE WITH RESPECT TO INPUT VOLTAGE

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A 4 000-kVA asynchronous cycloconvertor has recently been installed by the German State Railways to supply the Wiesenthal section of their railway system in Baden.* The equipment has a continuous rating of 3 600 kVA, and can carry 4 000 kVA for half hour and 6 000 kVA for one minute. It is designed to convert three-phase alternating current at 45 kilovolts and 50 cycles, obtained from the Rheinfelden Power Transmission Co.'s supply network, to single-phase alternating current at 17 kilovolts and $16\frac{2}{3}$ cycles as required by the traction system. The power factor of the traction load is normally $\cos \phi = 0{\cdot}7$, under which condition the full-load efficiency of the cycloconvertor is 90 per cent. At half load the overall efficiency attains 91 per cent. The power factor, i.e. the ratio of kW to kVA, on the three-phase side is $\lambda = 0{\cdot}6$ for $\cos \phi = 0{\cdot}7$. The all-day efficiency of this static frequency-converting unit, based on an average load factor of 30 per cent, is estimated at 83 per cent. This figure represents an improvement of 19 per cent as compared with modern rotating plant of the same output, and of no less than 26 per cent as compared with the existing converting plant which was installed in 1913.

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* *Cf. Elektrotechnisches Zeitschrift,* 1934, Vol. 55, p. 65; also *Elektrische Bahnen,* 1935, Vol. 11, p. 235; and *ibid.,* 1937, Vol. 17, pp. 191 and 203; and *A.E.G. Mitteilungen,* 1938, p. 66.

The Grid-Controlled Cycloconvertor. In spite of the undoubted advantages arising from good wave-form of the single-phase voltage, the Löbl and the Krämer cycloconvertor have one drawback in common, namely, that they operate with a fixed frequency ratio, the value of which is of necessity 3 to 1. And it is more than fortunate that the standard frequency for alternating-current traction supply on the Continent has become 16⅔ cycles per second, as otherwise there would have been little prospect of being able to develop such systems of cycloconversion to an extent which would allow of their general application to static frequency changing.

The synchronous type of envelope cycloconvertor has the further disadvantage of being applicable only in cases where generating plant is absent on the single-phase side. As a rule, the continental traction systems are supplied from their own power stations, so that the frequency of the single-phase system to which the cycloconvertor is connected bears no fixed relation to the frequency of the single-phase output from the cycloconvertor. For this reason the asynchronous type of cycloconvertor discussed in the preceding section is more likely to be of general application in linking up existing traction systems, operating at a frequency of 16⅔ cycles per second, with 50-cycle industrial power networks.

Both types of cycloconvertor, however, have in common an inherent functional weakness that is fundamental to the envelope method of static frequency changing. This disability, which is perhaps not immediately apparent from the mode of operation of such cycloconvertors, is the fact of their being limited in their capacity to transfer reactive power from the higher-frequency to the lower-frequency system. It is necessary to be clear on this point, about which a considerable amount of confused thinking prevails. In the envelope cycloconvertor the use of grid control extends *only* to preventing the operation of one rectifier unit during the half-cycle of lower frequency in which the other rectifier unit is carrying the single-phase load current. That is to say, *grid control is not essential to the correct functioning of such frequency convertors* (as may be observed from early patent specifications) but its adoption considerably simplifies the apparatus.

For such a cycloconvertor to supply an inductive load, it is a necessary condition of its operation that the individual rectifier units can carry at all instants in the lower-frequency voltage cycle the reactive as well as the active component of the load current. Assuming, for example, a single-phase load of zero power factor, this condition implies that each rectifier unit in turn must be in a position to carry current for a further one-quarter of a cycle beyond its normal operating period, i.e. the half-cycle corresponding to resistance-load working. In the case of normal rectifiers, it is manifestly impossible for such a condition to be fulfilled. But the provision of control grids, together with appropriate means of grid excitation, does permit a rectifier to be made conducting during the negative half-cycle of anode voltage; for upon this fact rests the principle of operation of the mercury-arc invertor.

To enable a cycloconvertor to transmit reactive power as well as active power, therefore, it is necessary that each of its two constituent rectifier units should operate as an invertor during certain periods of the lower-frequency cycle. That this must be so is evident from energy considerations alone. As explained in Chapter XIV, reactive power is characterized by the fact that it oscillates about zero mean value. That is to say, it represents a component of the total or apparent power which is periodically changing its direction, and at a frequency which is twice that of the alternating current. During one-quarter of the lower-frequency cycle, the cycloconvertor will therefore transfer a momentary excess of power to the lower-frequency circuit which it must be able to return to the supply system during the next quarter-cycle.

Static frequency arrangements which fulfil this requirement consequently operate in accordance with principles which differ fundamentally from those underlying the envelope cycloconvertor. The first indication of any practical form of cycloconvertor based on such principles appears to have been given by Hazeltine in 1923.* His original patent specification includes an arrangement of electric valves designed to operate in such a manner that by stringing together portions of voltage waves pertaining to a three-phase 50-cycle alternating-current system, composite voltage-waves alternating at a frequency of 10 cycles per second were obtained which, when taken in rotation, provided an essentially four-phase alternating-current supply. The main feature of such a method of frequency conversion is that the frequency ratio may be chosen at will, and thus depends only upon the particular way in which the valves are controlled. And it is for this reason that such static frequency convertors are termed *grid-controlled* cycloconvertors.

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* British Patent Specification No. 218675, dated 4th January, 1926. This patent lapsed in 1929.

The mode of operation of one such cycloconvertor—the variable-ratio cycloconvertor developed by Schenkel and von Issendorff* in 1931, and sponsored by the Siemens-Schuckertwerke A.G.—is perhaps best understood by considering the grid-controlled rectifier as applied to voltage regulation when converting alternating to direct current. If the grid-control gear is arranged to operate in such a manner that the direct-current output voltage of the rectifier is periodically varied from zero to a maximum and back again to zero, then it is possible in this way to generate a pulsating direct current, the frequency of the pulsations being lower than that of the alternating-current supply. Furthermore, if two such currents of opposite sense are allowed to pulsate alternately in an electric circuit, one obtains a simple alternating current. The frequency of this alternating current is determined by the frequency at which the output voltages of the two rectifiers—each of which generates a half-wave, as in Fig. 132—are varied from zero to a maximum and back to zero again. The theoretical waveform of the lower-frequency output voltage obtained from such a cycloconvertor, in the case of a 3 : 1 frequency ratio, is shown in Fig. 138. It is seen that each half-wave is built up of different portions of the successive half-waves of anode voltage, the average effect over the whole cycle being equivalent

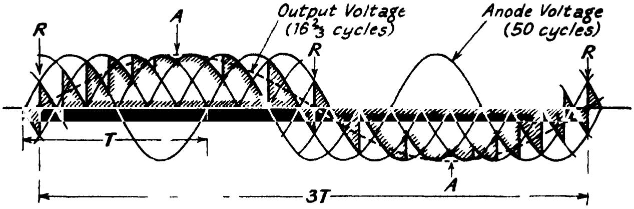

Fig. 138. Theoretical Output Voltage of the Siemens-Schuckert Variable-ratio Cycloconvertor
English Electric Co.

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* *Vide* M. Schenkel: "An Asynchronous System of Static Frequency Conversion for the Supply of Low-frequency Traction Networks," *Elektrische Bahnen*, 1932. Vol. 8, pp. 69–73.

to that of a true sinusoidal voltage. The magnitude of the effective portion of each anode-voltage wave is dependent on the phase angle of arc commutation which, in turn, is determined by the grid-control apparatus. As shown in Fig. 138, at the beginning and end of each half-cycle (R) the ignition of the arc is fully retarded, and the effective rectified voltage is a minimum; whilst at the middle of the half-cycle (A) the ignition is fully advanced and the effective rectified voltage is a maximum.

The required variation of the ignition angle may conveniently be obtained by bias-shift control of the grid potential, whereby a low-frequency, alternating bias potential is superimposed upon the polyphase grid-excitation voltage which is of normal supply frequency. The main connections of such a variable-ratio cycloconvertor designed to interconnect a three-phase 50-cycle power system with, say, a $16\frac{2}{3}$-cycle single-phase traction system are shown in Fig. 139. The power system supplies a transformer with two secondary windings which, in turn, supply two six-phase grid-controlled rectifier systems combined in a single container and with a common cathode. Each rectifier system supplies one-half of the primary winding of a single-phase output transformer, the secondary of which is connected to the lower-frequency traction network. Bias-shift control of the grid excitation is then obtained by means of a small single-phase control transformer energized from the lower-frequency supply.

From the above considerations it is clear that the characteristic operating feature of the variable-ratio cycloconvertor is that the wave-form of the single-phase output voltage is not determined before rectification takes place, as in the case of the envelope cycloconvertor, but is *actually generated during the rectification process* and is, in fact, the outcome of the peculiar way in which normal rectification of an alternating voltage may be modified by grid control. As a direct consequence of this characteristic mode of operation, the output voltage suffers a greater distortion than in the case of envelope cycloconvertors where natural commutation of the current arc takes place. But this distortion can be considerably reduced by employing twelve-phase rectifier systems. Even in the case of a six-phase cycloconvertor unit, however, the harmonic distortion occurring both in the output voltage and the input currents is actually much less than one would be led to expect from theoretical considerations alone, due to the inductive reactances inevitably present in the circuit. This is clearly illustrated by Fig. 140, which gives two oscillograms obtained with an 800-kVA cycloconvertor of this type. The upper oscillogram shows the three-phase input voltage and current (50 cycles per second) and the single-phase output voltage (16⅔ cycles per second) with a load of 490 kVA, whilst the lower oscillogram relates to a load of 560 kVA. It is particularly interesting to note in these oscillograms the pronounced reaction of the lower-frequency system upon the higher-frequency supply. It is seen that the alternative positive and negative blocks of primary current exhibit a regular and cyclic variation in magnitude, the frequency of this variation being that of the single-phase output. This characteristic feature of all systems of direct frequency changing, i.e. of

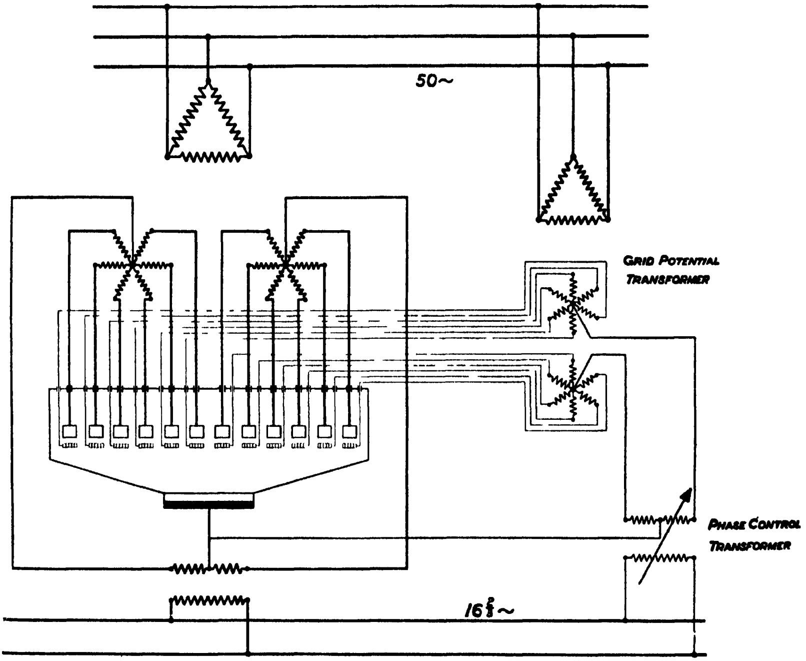
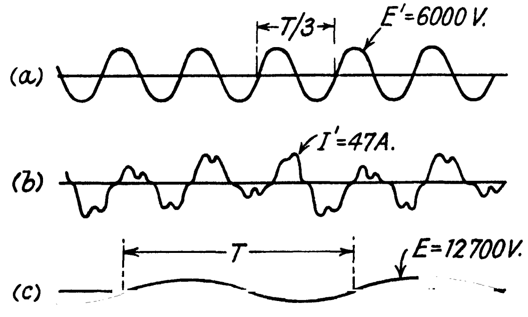


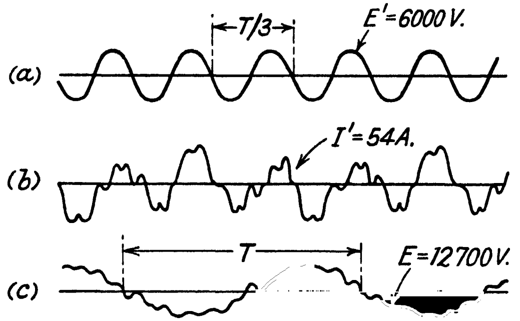
FIG. 139. CIRCUIT CONNECTION OF THE SIEMENS-SCHUCKERT VARIABLE-RATIO CYCLOCONVERTOR
English Electric Co.

cycloconversion, was referred to at the beginning of the present chapter, and is also indicated in Fig. 133.

That the variable-ratio cycloconvertor is fully capable of supplying the wattless power requirements of the lower-frequency network directly from the higher-frequency system is



(A) Single-phase Output: 490 kVA.



(B) Single-phase Output: 560 kVA.

FIG. 140. ACTUAL CURRENT AND VOLTAGE WAVE-FORMS OBTAINED WITH AN 800-KVA CYCLOCONVERTOR

(a) = Input voltage (b) Input current (c) — Output voltage

Siemens-Schuckertwerke

clear from Fig. 141. Here e represents the lower-frequency voltage wave, and i_1 a reactive current lagging by 90 degrees; or i_2 is a reactive current leading by 90 degrees. It is seen that the rectifier system which provides the positive half-wave of the voltage e must be capable of delivering current already before the commencement, and even after the completion of the voltage half-wave. In other words, the supply of current from the rectifier system is by no means limited to a half-period, as is the case where the cycloconvertor is supplying a non-inductive load. Each rectifier, then, must be in a position to supply current during any part of the output-voltage cycle. For this reason grid control is essential to permit of current flow through each rectifier during its negative half-period of anode voltage, provided that the available voltage of the output circuit is sufficient to drive a current through the rectifier under these conditions. As may be seen from the illustration, the reactive current i_1, for example, does not cease to flow when e passes through zero. By means of grid control the rectifier can be made to deliver current during the negative half-cycle of anode voltage so that the current i_1 continues to flow until it reaches zero value of itself. During this latter period the commutation of the current arc from one anode to the next is forced, as in the case of inverted operation of the ordinary rectifier. This state of affairs is indicated by the arrows in the diagram.

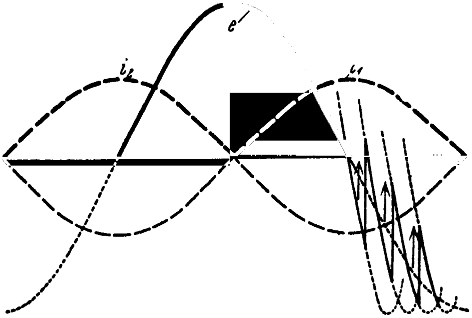


FIG. 141. TRANSMISSION OF REACTIVE POWER THROUGH THE SIEMENS-SCHUCKERT VARIABLE-RATIO CYCLOCONVERTOR
George Newnes Ltd.

The ability of the variable-ratio cycloconvertor to supply any desired amount of reactive power to the lower-frequency system is a factor of very great importance, and constitutes one of the main advantages of this method of static frequency changing.

Fig. 142 shows the operating characteristics of the 800-kVA cycloconvertor unit previously referred to in connection with Fig. 140, when supplying a traction-motor load of power factor cos $\phi = 0{\cdot}95$, and for two values of the output voltage. It is seen that the power factor on the three-phase side varies but little with the load, as is to be expected in the case rectifier equipment. On the other hand, due to the use of grid control for varying the single-phase voltage and therewith the power output of the cycloconvertor, the primary power factor falls in proportion to the reduction in output voltage. A 2 500-kVA cycloconvertor of this type has recently been installed in the Saalach power station of the German State Railways.*

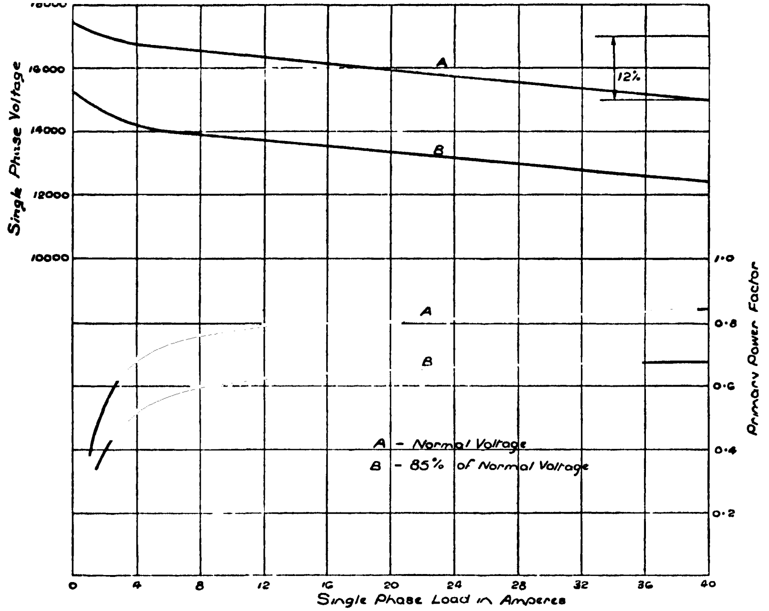


FIG. 142. OPERATING CHARACTERISTICS OF THE 800-KVA CYCLOCONVERTOR
English Electric Co

Mention should perhaps also be made here of a further type of cycloconvertor very recently developed by Heppner and Kantorowicz,† which was awarded the prize given by the German State Railway authorities in 1933 for the most promising system of asynchronous frequency conversion employing static apparatus. The principal connections of this ingenious cycloconvertor are given in Fig. 143. The three-phase supply is transformed to a six-phase supply at the 50-cycle bus-bars of the cycloconvertor unit. Each bus-bar feeds three phases of

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* See *Elektrische Bahnen*, 1934, Vol. 10, p. 10; and *ibid.*, 1935, Vol. 11, p. 235.

† German patent application dated 18th January, 1933.

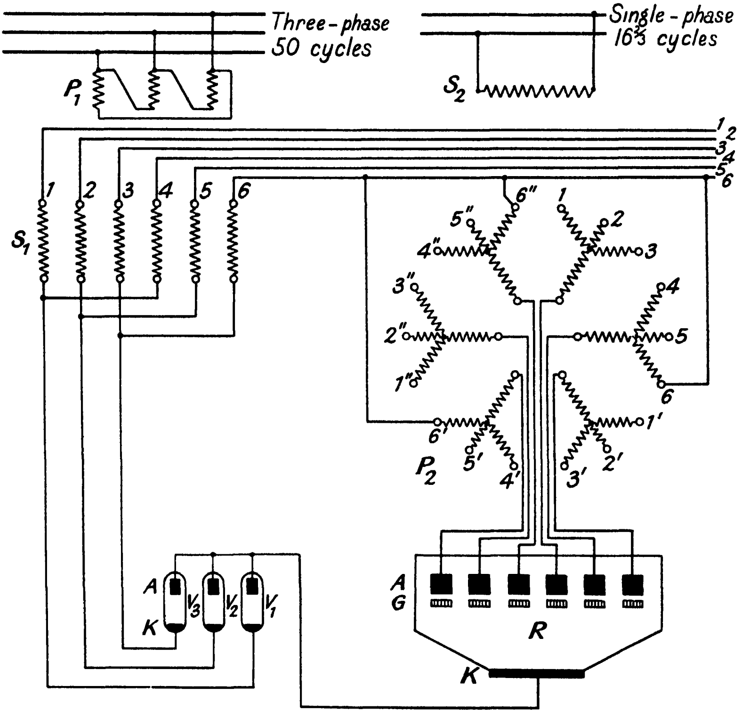

FIG. 143. FUNDAMENTAL CIRCUITS OF THE HEPPNER VARIABLE-RATIO CYCLOCONVERTOR

the eighteen-phase primary winding P_2 of the output transformer, the three phases being displaced in phase from one another by 120 electrical degrees as shown. The neutral points of this secondary winding are brought out to a six-phase grid-controlled rectifier R, the cathode of which is connected to the anodes of three single-phase rectifying valves, V_1, V_2 and V_3. These may conveniently be of the hot-cathode type. The cathodes of these valves are in turn connected to the three neutral points of the six-phase transformer secondary S_1. The secondary winding S_2 of the output transformer is shown single-phase, but may equally well be arranged as a three-phase winding.

The mode of operation of the cycloconvertor is briefly as follows: As each one of the bus-bars is connected to three symmetrically-spaced points on the periphery of the transformer winding P_2, these three points will always be at the same potential, and will be positive simultaneously once in every cycle of primary frequency. By appropriate grid control of the rectifier *R* it is arranged that only one of these three phases is allowed to carry current at a time, the three being taken in rotation; so that once in every three cycles of primary frequency each phase of P_2 delivers current from the bus-bars to the rectifier *R*. As the result, the cyclical frequency of the phase voltages generated in the primary winding of the output transformer is one-third that of the three-phase supply, and the secondary winding S_2 therefore delivers a sinusoidal output at $16\frac{2}{3}$ cycles per second.

As far as the author is aware, financial considerations have so far prevented the German State Railway authorities from pursuing the development of this new cycloconvertor to a commercial stage, particularly in view of the fact that a large measure of success has already been achieved with both the envelope and the grid-controlled types of static frequency convertors.

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(3) H. Laub: *Archiv fur Elektrotechnik*, 1933, Vol. 27, p. 215.
(4) O. Lobl: *Zeitschrift des Vereins Deutscher Ingenieure*, 1933, Vol. 77, p. 685.
(5) M. Schenkel: *Elektrische Bahnen*, 1932, Vol. 8, p. 69.

CHAPTER XIII

MISCELLANEOUS TYPES OF ELECTRIC DISCHARGE DEVICE

Up to the present we have considered only those applications of the electric discharge device in which the amount of power handled by the apparatus is considerable. But it must not be thought, therefore, that, because they are perhaps the most imposing, such power applications are the most important. In our natural enthusiasm for the spectacular, in engineering achievement no less than in matters of daily life, we are rather apt to forget that the control of power is of scarcely less moment than are its generation and conversion; and that in consequence the development of the relay—electricity's "lever," whereby a small effort may be translated into a much larger force—has come to occupy a foremost position in our electrical engineering technique.

The majority of relays operate by essentially electro-mechanical means, and we have thus become accustomed to thinking in terms of this particular type of apparatus when considering the possibilities of relay action. But if we accept the definition that a relay is a device whose function is to enable electric power in considerable quantity, as carried by a heavy current at normal voltage, for example, to be controlled by a relatively small amount of energy, such as that associated with a flash-lamp battery, to cite another example, then we must admit devices as widely separated in operating principle as the photo-electric cell and the thermionic valve to the general category of electric relay.

The Gas-discharge Relay or Grid-glow Tube. A static relay of a particularly useful type is the grid-glow tube developed by the American Westinghouse Co. In appearance it somewhat resembles the familiar thermionic triode or wireless valve, to give it its everyday name. Like the latter, it comprises three electrodes—a cathode, an anode, and a grid. But there the similarity ends. In the first place, the grid-glow tube is a gas-discharge relay and not a vacuum relay. After evacuation of the glass envelope forming the body of the tube, a certain amount of inert gas, usually neon or argon, is admitted; so that the grid-glow tube has electro-physical characteristics differing markedly from those of the vacuum tube; and, in the second place, the tube is of the cold-cathode type and thus requires no extraneous means of furnishing the requisite electron emission.

In essence, then, the grid-glow tube is a neon lamp provided with a control grid. The conditions inside such a tube when a potential is applied between anode and cathode are illustrated in Fig. 144. When the potential exceeds a certain critical value—generally known as the *breakdown voltage*—a discharge occurs between anode and cathode. The breakdown voltage is a function only of the electrode spacing and of the gas pressure, the relation being known as *Paschen's Law.** The discharge current attains a value of several milliamperes, whereas previous to its incidence the current flow through the tube was of the order of microamperes only. And in such a tube the discharge takes place as a glow between anode and cathode which may be divided into several distinct parts as shown in Fig. 144.

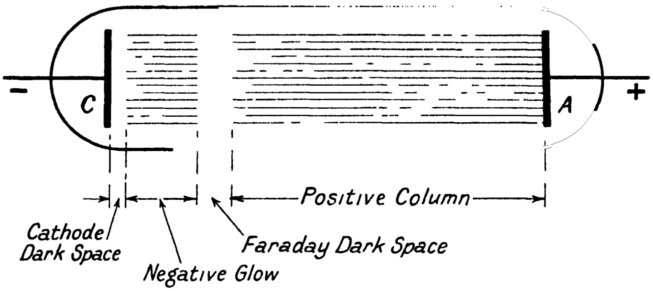

FIG. 144. ELEMENTS OF THE GLOW DISCHARGE

Immediately adjacent to the cathode and completely surrounding it is a well-defined region of feeble luminosity known as the *Crookes' dark space.* Almost the entire voltage drop across the tube is concentrated in this region, which is traversed by the electrons emanating from the cathode. In this initial stage of their journey to the anode, the electrons are accelerated to very high velocities and reach speeds great enough for them to ionize the gas by collision with neutral atoms. Next to the dark space near the cathode is a luminous region, called the *negative glow*, where recombination of electrons and ions takes place, during which process the energy liberated manifests itself as a yellowish-pink light. Following upon this negative glow is a further region of very low luminosity and known as the *Faraday dark space*; and between this and the anode there extends, finally, another luminous part of the discharge referred to as the *positive column.*

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* *Cf.* J. J. Thomson: *Conduction of Electricity Through Gases,* p. 367.

The chief feature of such a glow discharge is that the first three regions are unaffected by any increase in distance between anode and cathode. Their relative distribution is determined by the pressure and nature of the gas content of the tube. The effect of lengthening the discharge path is merely to increase the length of the positive column, so that the latter may be regarded simply as a gaseous conductor forming an extension to the anode. If the anode is brought nearer to the cathode, thus shortening the discharge path, the positive column shrinks until eventually it disappears altogether. It is this condition which obtains in the grid-glow tube.

If a grid is inserted in the discharge path it will not assume a potential equal to that of the corresponding point in the discharge. Due to the larger mass of the ions present in the discharge path, their velocity is much lower than that of the electrons. Consequently the grid will be struck by very many more electrons than ions in any given length of time. As the result, the potential assumed by the grid is more negative than would be that of the same region were the grid removed from the discharge path. In the grid-glow tube the grid is so placed that electrons reach it in large numbers and at high speeds, whilst the relatively sluggish positive ions arrive in small numbers and attain comparatively low velocities.

Now the glow discharge proper, which occurs almost immediately after the voltage across the tube has reached the critical or breakdown value, is preceded by a form of discharge which is not self-supporting. To begin with, the discharge path is occupied by only a relatively small number of ions and electrons, which are the products of natural ionization. As the tube voltage is raised, the electrons are accelerated, so that increasing ionization takes place. The discharge current consequently increases, and does so with a stable characteristic, until it reaches a value known as the *threshold current,* which corresponds to the breakdown voltage of the tube. Beyond this point the discharge becomes unstable, and the current increases rapidly whilst the voltage drop across the tube falls. In other words, the discharge then becomes self-supporting and develops into a complete glow discharge. The threshold current is that current necessary for maintaining the critical degree of ionization in the discharge path, and amounts to a few microamperes only. In the grid-glow tube it is the function of the grid to reduce the effective ionization by absorbing the positive ions in the discharge path and repelling the electrons emanating from the cathode. In this way the grid provides a very sensitive means of controlling the threshold current and therewith the establishment of the self-supporting glow discharge.

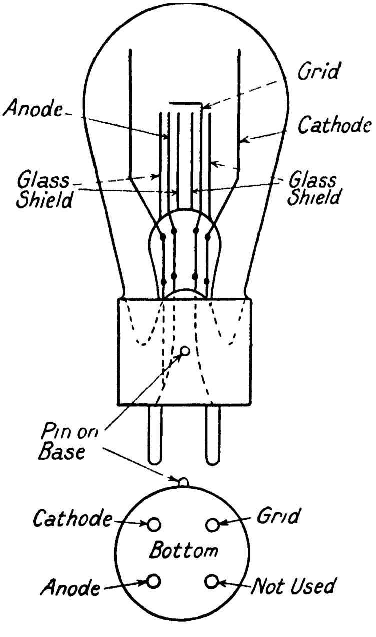
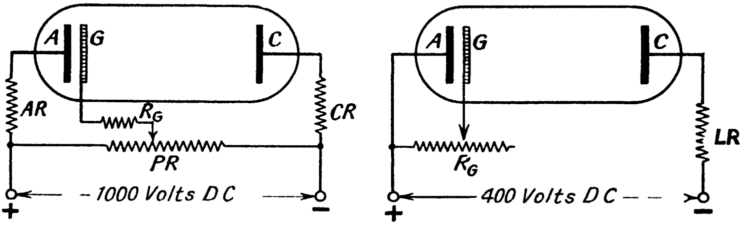


Fig. 145. Assembly of Typical Grid-glow Tube

In the grid-glow tubes developed by Knowles in the laboratories of the Westinghouse Electric and Manufacturing Co. (Fig. 145) the gas content is neon at a pressure corresponding to a few millimetres of mercury column. To ensure effective control, the spacing between anode and grid is made very short compared to that between anode and cathode. The breakdown voltage between anode and grid is much higher than that between grid and cathode, standard values with direct current being 1 000 volts and 400 volts respectively. Such tubes in consequence lend themselves to methods of grid-bias control as shown in Fig. 146. In diagram (*a*) a potentiometer *PR* is connected across the direct-current supply to the tube, the adjustable tapping being connected to the grid through a suitable limiting resistance R_G. The tube is protected by further current-limiting resistances *AR* and *CR* in series with the supply. By adjusting the potentiometer tapping so that the voltage between *G* and *C* is less than 400, a breakdown in this region is prevented, whilst the remaining 600 volts is insufficient to break down the discharge path between *A* and *G*. On altering the tapping so that the voltage between *G* and *C* exceeds 400, a self-supporting discharge takes place in the grid-cathode space, and, under the influence of the intense field between *G* and *A*, it is immediately transferred to the anode, thus completing the relay action of the tube. According to Knowles, the threshold current may be taken as 2 mA, and the potential drop across the glow discharge as 300 volts. The net e.m.f. in the grid circuit during the discharge is thus 100 volts, so that the limiting resistance R_G should have a value of 50 megohms.



(a) Potentiometer Control (b) Self-bias Control

FIG 146. CONTROL CIRCUITS FOR GRID-GLOW TUBES

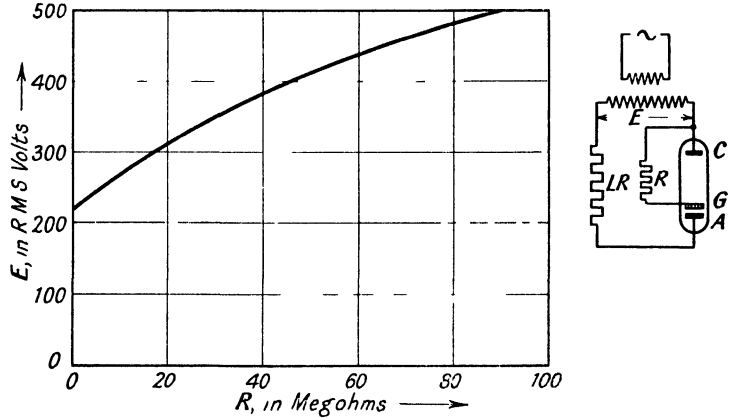


FIG. 147 CONTROL CHARACTERISTICS OF TYPICAL GRID-GLOW TUBES

An alternative method of controlling a grid-glow tube is illustrated in Fig. 146 (*b*). As has already been explained, the grid assumes a potential more negative than that corresponding to the point in the discharge where the grid is situated. By connecting a high-resistance R_G between grid and anode, the negative charge on the grid will tend to leak away and, in consequence, the discharge current between cathode and grid will increase in order to restore the grid potential to its initial value. By reducing the resistance of the grid-leak R_G the cathode-grid current can be increased until it reaches a value equal to the threshold current, when the discharge becomes self-supporting as before. As shown in diagram (*b*) of Fig. 146, a limiting resistance *LR* is connected in series with the tube to limit the discharge current to the value for which the tube is designed, and varying in practice from 10 to 50 mA. A method of operating such a tube which immediately suggests itself is to employ a photo-electric cell as the grid-leak. Fig. 147 shows the relation between circuit voltage and grid-leak resistance for a typical grid-glow tube (Westinghouse type GS. 18).

The Hot-cathode Mercury-vapour Rectifier.* Until comparatively recently the technique appropriate to the control of large powers by means of static apparatus has been limited to two classes of rectifying device, namely, the high-vacuum thermionic rectifier and the arc rectifier with mercury cathode. In the former type of electric valve the discharge between anode and cathode takes place in space that is essentially free from gas or vapour, whilst in the latter type the discharge occurs in a rarefied vapour atmosphere. Moreover, in the case of the thermionic rectifier, the discharge current is carried entirely by the electrons emitted from the cathode; but in the case of the arc rectifier, the discharge current manifests itself as a high-intensity arc consisting of electrons and positive ions streaming in opposite directions. And, as was explained in Chapter II, the characteristic difference between these two forms of electric discharge is that in the one case currents of the order of a few amperes are associated with a pressure drop of several thousand volts, whilst in the other case thousands of amperes are associated with a pressure drop of only a few volts.

The synthesis of these two types of electric valve has resulted in the development of a thermionic rectifier operating in an atmosphere of mercury vapour at extremely low pressures. This hybrid rectifier—termed *hot-cathode mercury-vapour rectifier*, but generally known as *hot-cathode rectifier* simply—made its first appearance in practical form in 1928,* although repeated attempts had previously been made to produce a commercial rectifying device which would combine the simplicity of the thermionic rectifier with the efficiency and current-carrying capacity of the mercury-arc rectifier. The chief difficulty encountered in the development of this new rectifier lay in obtaining a reasonable life from the cathode. The vapour atmosphere, although it enabled a low voltage-drop between anode and cathode to be obtained, consequent upon ionization in the discharge path, unfortunately produced disintegration

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* Also known as the *Phanotron*—the name given by the American General Electric Co.

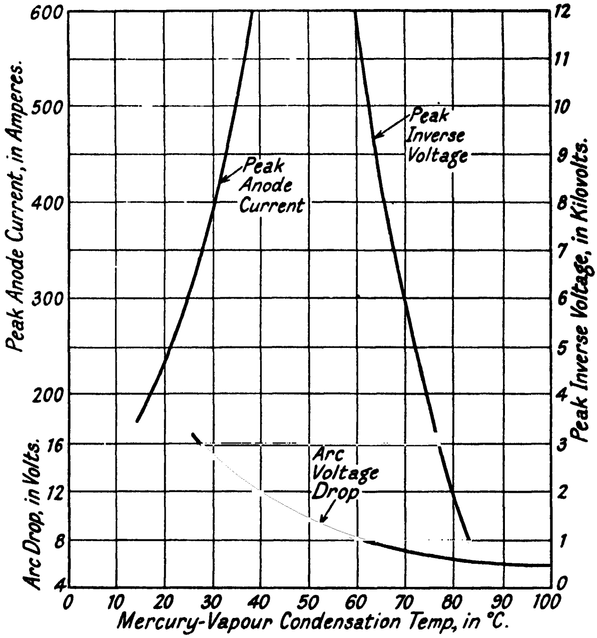

FIG. 148. CHARACTERISTICS OF HOT-CATHODE MERCURY-VAPOUR RECTIFIERS

of the electron-emitting layer* at the surface of the cathode due to incessant positive-ion bombardment. Finally, Hull discovered that the positive ions carried by the discharge current can only cause cathode disintegration if the mean kinetic energy they acquire in traversing the electric field between

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* Vide *Transactions of the American Institute of Electrical Engineers*, 1928, Vol. 47, p. 755.

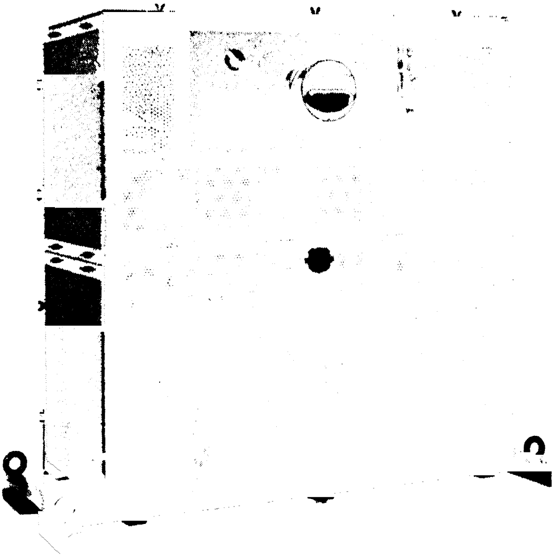

FIG. 149. 75/75-A, 110-V HOT-CATHODE RECTIFIER UNIT
Lancashire Dynamo & Crypto Co.

anode and cathode exceeds a definite minimum value. This value of kinetic energy corresponds to a certain critical voltage between anode and cathode, which Hull has termed the *disintegration voltage.* For a given cathode design and gas or vapour pressure, this voltage depends only upon the nature of the gas or vapour introduced into the discharge space. For mercury vapour the disintegration voltage is 22 volts, whilst the ionization potential is only 10·4 volts. It is therefore possible, by introducing the correct quantity of mercury into the rectifier bulb, to obtain a voltage drop between anode and cathode which is considerably below the disintegration voltage. At any rate, the important point to be noted is that, to quote Hull, "there exists a voltage below which positive ions cause no cathode disintegration" and that "this voltage is sufficiently above the ionization potential so as to provide between them a practical operating range."

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* The early cathodes consisted of "thoriated" tungsten filaments whose electron emission arises mainly from a layer of thorium, one atom thick, on the surface of the tungsten. Subsequently the Wehnelt type of cathode was developed in which a nickel filament is covered with a coating of barium or caesium oxide. It would appear, however, that the electron emission is due not to the oxide but to a monatomic film of the alkaline earth metal bound to the nickel surface.

In commercial hot-cathode rectifiers the internal potential drop amounts to 12 or 15 volts (Fig. 148), so that such rectifiers are more efficient than the mercury-arc type at low direct-current pressures. For example, at 100 volts a hot-cathode rectifier shows an efficiency of 88 per cent, whilst a mercury-arc rectifier has an efficiency of only just over 80 per cent. For this reason hot-cathode rectifier equipments are widely used for battery charging and for supplying low-voltage direct current to the projection arcs in cinema theatres. Fig. 149 illustrates a 75/75-A, 110-V twin rectifier unit as manufactured by the Lancashire Dynamo and Crypto Co. for supplying a pair of cinema projector arcs. Fig. 150 on the following page illustrates a six-circuit electric vehicle battery charger of the hot-cathode rectifier type manufactured by Messrs. Philips Industrial Ltd. The operating characteristics of a 10-A, 220–230-V Philips equipment are shown graphically in Fig. 151.

The Grid-controlled Mercury-vapour Valve.* Inasmuch as the hot-cathode mercury-vapour rectifier is the outcome of the synthesis of the thermionic and mercury-arc types of rectifier, so also is the grid-controlled mercury-vapour valve a hybrid—being, in fact, the three-electrode counterpart of its prototype. A more correct title for this comparative newcomer to the field of applied electronics would perhaps have been "mercury-vapour triode" by analogy with the vacuum triode; although the cognomen "thyratron" appears to have received considerable support on this side of the Atlantic as well.

The operating features of the grid-controlled mercury-vapour valve, then, are those which one would expect of a hot-cathode

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* Generally referred to as the *Thyratron* (from the Greek *θυρα*, meaning *a door*)—the name adopted by the American General Electric Co.

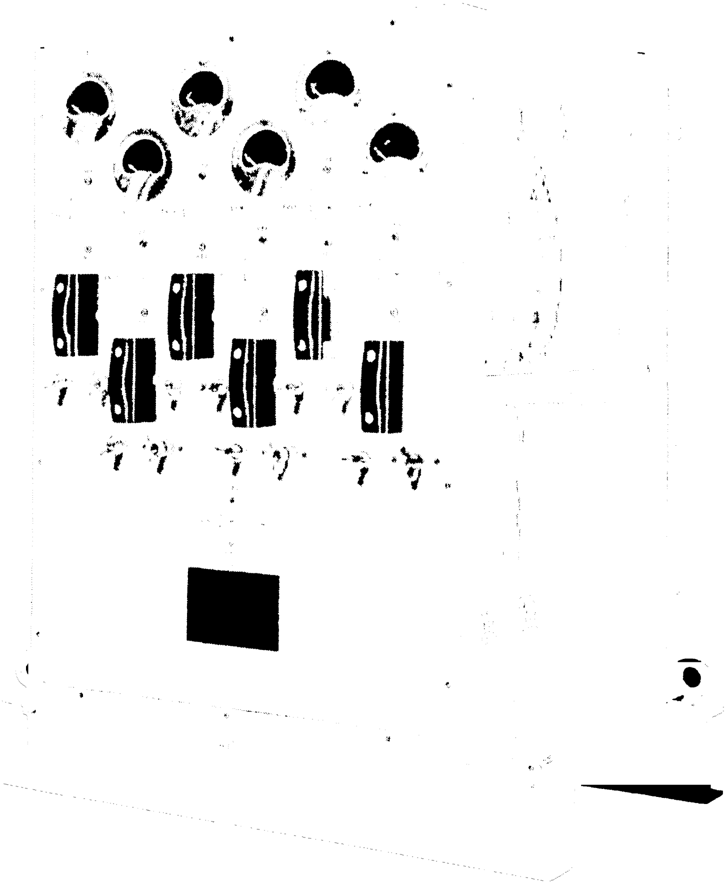

FIG 150 TYPICAL HOT-CATHODE RECTIFIER EQUIPMENT

Philips Industrial Ltd

Exterior view of six circuit battery charger rectifier provided with a control grid. As was explained in the previous section, the hot-cathode rectifier behaves in a manner akin to the mercury-arc rectifier; so that the grid-controlled mercury-vapour valve exhibits control characteristics that are comparable with those obtaining in the case of the grid-controlled mercury-arc rectifier. The only real difference between these two types of controlled arc-discharge device lies in the relation between the anode voltage and the critical grid potential. As may be seen from curves 1, 2, and 3 of Fig. 66, the critical grid potential of the mercury-arc type is sensibly independent of the anode voltage. On the other hand, curves 4, 5 and 6 indicate that, in the case of the hot-cathode type, the critical grid potential decreases with increasing anode voltage, i.e. the greater the value of the anode potential, the more negative will be the critical potential applied to the grid which

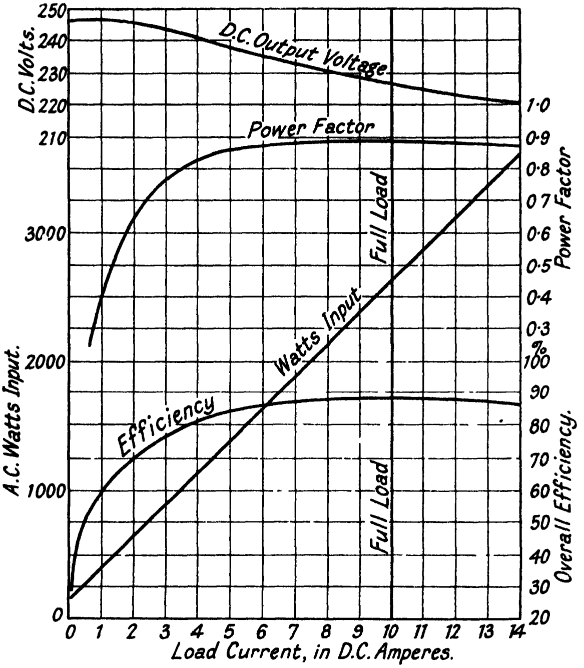

FIG. 151. OPERATING CHARACTERISTICS OF 2-KW HOT-CATHODE RECTIFIER UNIT

Philips Industrial Ltd.

will just prevent the arc discharge from establishing itself. From a practical point of view, however, this distinction is of little importance.

Up to the present, grid-controlled mercury-vapour valves have appeared only in the glass-bulb form, typical small valves of this type being illustrated in Fig. 152 and Fig. 153. On the Continent these valves have reached a fairly high stage of development, as may be seen from Fig. 154. The little tube on the left is capable of handling half an ampere at 5 000 volts (peak). The one in the centre is rated at 200 A, whilst that on the right is designed to carry 1 000 A during the permeable half-cycle. The permissible peak inverse voltage for these latter is stated to be 15 000 volts. No experience has as yet been gained with a steel-tank type of construction for these valves, although large thermionic transmitting valves of the all-metal type have been in use for many years in high-powered wireless stations. A design of steel-tank hot-cathode mercury-vapour rectifier has actually been put forward in Germany,*

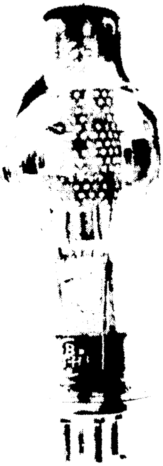

FIG. 152. B.T.-H. THYRATRON TYPE B.T.7

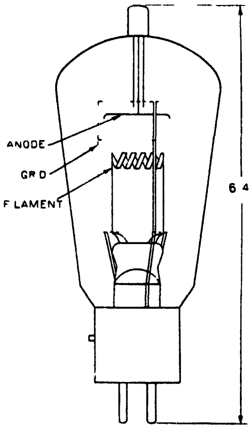

FIG. 153. B.T.-H. THYRATRON TYPE B.T.

British Thomson-Houston Co.

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* Vide *Elektrotechnische Zeitschrift*, 1932, Vol. 53, p. 780, Fig. 29.

and the special cathode construction employed is such that the sponsors of this latest development claim current ratings of 10 000 A as possible. At the same time it seems doubtful whether a reasonable cathode life can be expected under such conditions.*

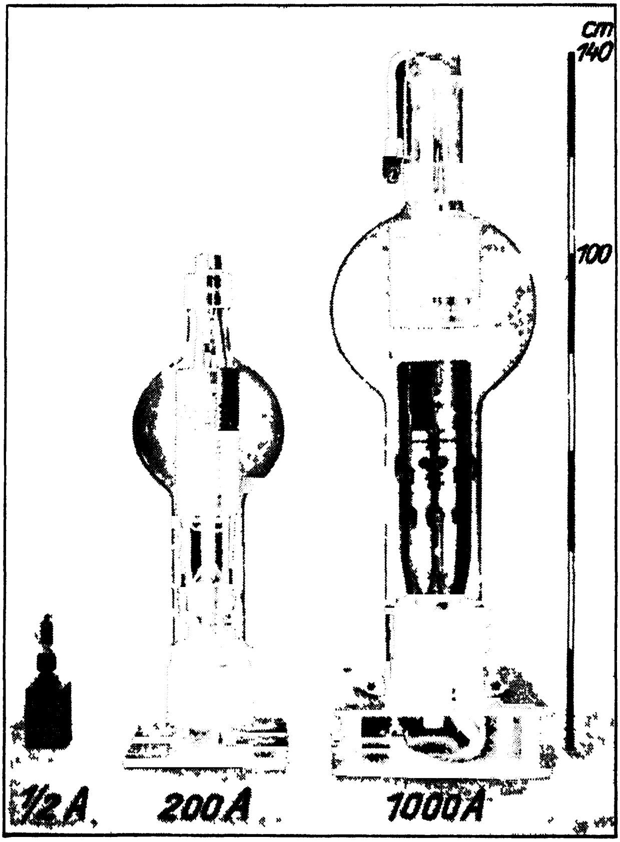

FIG. 154. SOME EXAMPLES OF A.E G THYRATRONS
A E G Electric Co.

The methods of grid-control applied to the mercury-arc rectifier are, of course, equally applicable to the hot-cathode rectifier. By far the most widely used arrangement is that depicted in Fig. 155. Here phase-shift control of a sinusoidal grid voltage is obtained by means of a capacitance C in series with a resistance R, either or both of which may be variable. As will be seen from the vector diagram, the ignition angle is adjustable between 0° and 180°; whilst the grid voltage E_G is equal to half the secondary voltage E of the grid-excitation transformer.

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* In the case of the glass-bulb type the useful life of such valves averages 6 000 hours, as compared with 15 000 hours for glass-bulb mercury-arc rectifiers.

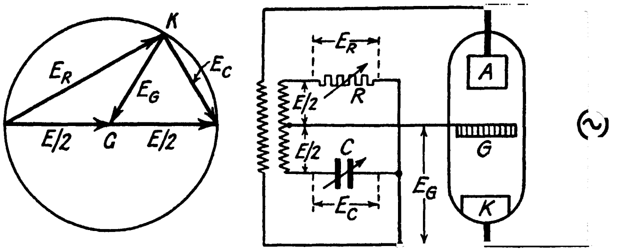

FIG. 155. PHASE-SHIFT CIRCUIT FOR A GRID-CONTROLLED MERCURY-VAPOUR VALVE (THYRATRON)

A practical example illustrating the application of bias-shift control to regulate the output voltage from a pair of grid-controlled mercury-vapour valves is the system of automatic voltage regulation developed by the American General Electric Co. for small alternators, and shown in Fig. 156. The voltage-sensitive element controlling the grid potentials is an alternating current bridge of dissimilar resistances, of which one diagonal pair RR may be wire resistances, having a linear voltage/current characteristic, but the other pair $R'R'$ are non-ohmic resistances, for which the relation between voltage

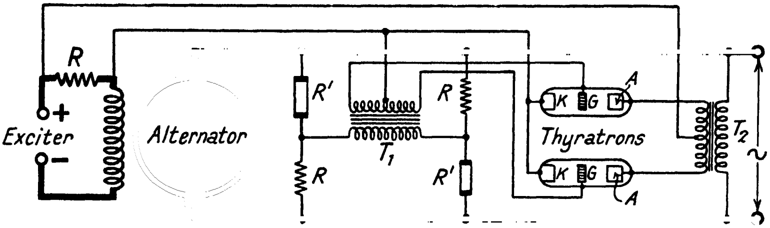

FIG. 156. THYRATRON VOLTAGE REGULATOR FOR 15-KW ALTERNATOR
American General Electric Co.

and current is not linear.* Since the resistances follow different laws, it is clear that the bridge will be balanced for only one value of the alternator voltage. When this condition obtains, the grids of the valves are at zero potential and each valve is made conducting for about half of the permeable half-cycle. At other values of the alternator voltage the bridge is unbalanced and a voltage is applied to the grids through the transformer T_1. This transformer is connected in such a sense that a rise in alternator volts makes the grids negative during their respective permeable half-cycles, thus preventing the valves from passing current and so decreasing the alternator field current. Conversely, a fall in alternator volts makes the grids positive, thereby rendering the valves operative during the major part of their respective permeable half-cycles, and thus causing them to supply more current to the alternator field than that normally supplied by the exciter through the resistance *R*. The entire absence of mechanical inertia makes this system of voltage control remarkably free from hunting or overshooting of the voltage due to sudden changes in load.

Fig. 157 illustrates a method of maintaining constant temperature by means of a grid-controlled mercury-vapour valve. (As in the case of Fig. 156, the auxiliary heating circuit for the cathode has been omitted for the sake of simplicity.) In this arrangement, also employed by the American General Electric Co., the temperature-sensitive element is an alternating-current bridge comprising two pairs of like resistances *RR* and *R'R'*. One resistance of one pair is of the pyrometer type and is located inside the furnace whose temperature it is desired to control. The heating winding *H* is connected to the power supply through a contactor *C*, the solenoid of which is energized by the valve current. Normal temperature corresponds to a balance of the bridge. A rise in temperature unbalances the bridge in such a way that the grid voltage is negative during the permeable half-cycle, thus rendering the valve non-conducting and causing the contactor to open. Similarly, a fall in temperature holds the contactor closed. In this way it is possible to maintain the temperature of a large furnace constant within ten degrees at 800° C. An alternative method of temperature control consists in supplying the heating winding directly from the valve, and continuously varying the value of the heating current by means of phase-shift control.

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* *E.g.* contact resistances, such as the "Rectox" metal rectifier; crystal detectors of various kinds; or resistances consisting of a conducting material dispersed in an insulating matrix, whose current may vary as the cube or even higher power of the voltage.

From the foregoing examples it will be appreciated that the grid-controlled mercury-vapour valve has opened up an entirely new line of approach to the many and varied problems associated with the control of electric power. In the solution which it affords to such problems it has the additional advantages of instant response to the controlling force; high overall efficiency, ranging from 95 to over 99 per cent; silence in operation and freedom from vibration; and, most important of all, great sensitivity combined with the utmost flexibility.

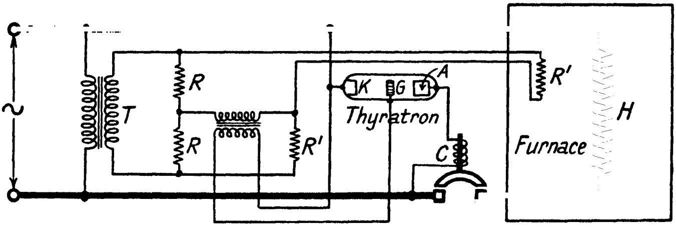

FIG. 157. THYRATRON REGULATOR FOR CONTROLLING THE TEMPERATURE OF A RESISTANCE FURNACE
American General Electric Co.

The Ionic Amplifier.* When considering the controlling function of a grid located in the path of an arc discharge, it was seen† that under certain conditions of field distribution the grid is able to regain control, when at a negative potential, without its being necessary to remove the driving e.m.f. of the discharge, i.e. the potential existing between anode and cathode. In other words, it is possible, by the choice of appropriate conditions of vapour pressure and electrode spacing, to create a situation in which the reimposition of a negative potential upon the control grid leads to a reduction of the discharge current, if not to the actual extinction of the arc.

Such a state of affairs obtains in the ionic amplifier developed by Lübcke and Schottky,‡ whose operation is analogous to that of the ordinary wireless valve. It is an arc-discharge device like the grid-controlled mercury-vapour valve. But, unlike the latter, the control exercised by the grid is both continuous and reversible—as in the case of the vacuum valve. The reason why the discharge current is a continuous function of the grid potential, so that the "mutual" characteristic of the valve can be traversed in either direction both in the positive and negative regions of grid voltage, becomes apparent on investigating the field distribution in the immediate vicinity of the grid. In the ionic amplifier the grid is of the wire-mesh type and is very close to the anode, as shown diagrammatically in Fig. 158, whilst the spacing of the grid wires is also very

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* Manufactured by Messrs. Siemens & Halske A.G. under the name of *Wandstromverstärker*.

† *Vide* Chapter VIII, pp. 164 *et seq.*

‡ Cf. *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1930, Vol. 9, pp. 390 *et seq.*

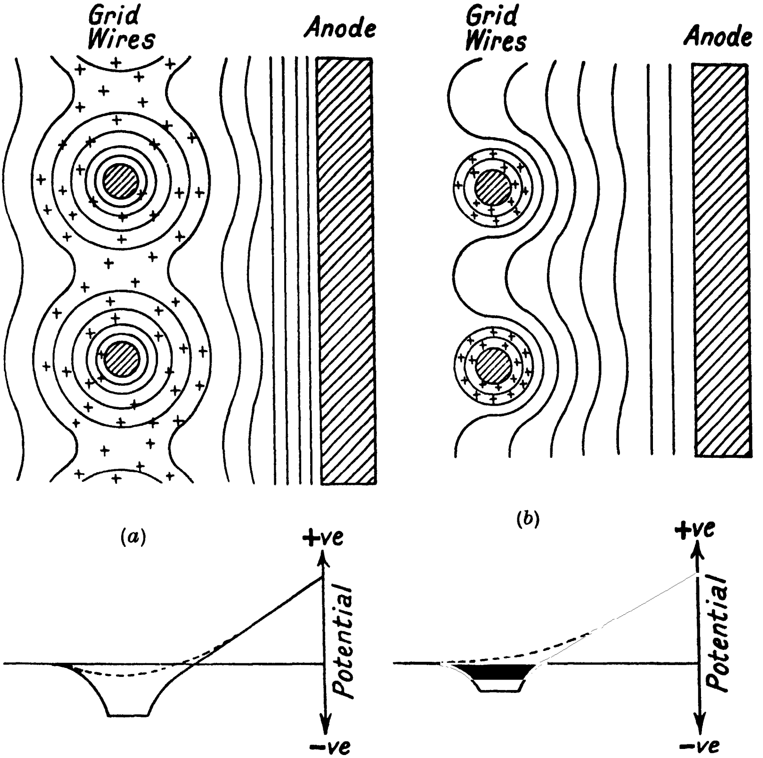

FIG. 158. POSITIVE-ION DISTRIBUTION IN THE VICINITY OF THE GRID

(a) Grid bias strongly negative (b) Grid bias slightly negative close. Let us assume that an arc has been established, so that the grid is immersed in the discharge, which contains approximately equal numbers of ions and electrons per unit volume (about 10^{10} per cubic centimetre). If now a strong negative potential be applied to the grid, the electrons travelling towards the anode will be repelled by the grid. On the other hand, the positive ions wandering towards the cathode are attracted by the grid, and give up their charge to it upon reaching its surface. The process is manifested by the flow of a positive grid current which, however, attains only a fraction of a milliampere per square centimetre of grid surface, due to the repelling influence of the dense cloud of positive ions which immediately forms around the grid wires.

The thickness of this positive space-charge is about 600 times less than that of the corresponding negative space-charge in a vacuum valve, assuming the discharge current to be the same in both cases. The mercury-vapour pressure and the design of the grid are so chosen that the positive space-charges surrounding individual grid wires are contiguous, as may be seen from the disposition of the equipotential lines in diagram (*a*) of Fig. 158. The lower part of the diagram indicates two sections through the electric field; firstly, along a line drawn through the grid wire (continuous line) and, secondly, along a line drawn through a point midway between two adjacent grid wires (dotted line). It is seen that the resultant potential in the interstices of the grid is negative, so that electrons leaving the cathode cannot penetrate the grid. Only those electrons present in the space between grid and anode can reach the latter and give up their charge. Thereafter this space becomes devoid of electrons, with the result that the anode current falls to zero. The valve is non-conducting.

On reducing the negative grid-potential, the thickness of the positive space-charge surrounding each grid wire diminishes correspondingly until the condition illustrated by diagram (*b*) of Fig. 158 is reached. The several positive space-charges are no longer contiguous and consequently the resultant potential in the interstices of the grid rises to a positive value, as indicated by the dotted potential line in the lower part of the diagram. The electrons leaving the cathode are now able to penetrate the grid and to reach the anode, and, in so doing, can carry a considerable current. In this way, altering the thickness of the positive space-charge around each grid wire by varying the grid potential causes a continuous variation in the number of electrons reaching the anode, that is, of the discharge current.

The point to be noted is that, in the case of the ionic amplifier, the anode-grid spacing is made small enough to prevent ionization of the vapour molecules in that space due to impact of the electrons penetrating the grid. In the grid-controlled mercury-vapour valve (*thyratron*), on the other hand, the distance between grid and anode is much greater, so that the mercury vapour in the anode-grid space suffers ionization by collision of electrons with neutral vapour molecules, in consequence of which the discharge becomes self-supporting and can no longer be influenced by the grid. These considerations lead to a design of valve depicted in Fig. 159. The production of the necessary electrons and positive ions is provided by an arc maintained between the mercury cathode *K* and the excitation anode *EA*. The anode *A* and control grid *G* are located on the periphery of this arc, the distance between them being only a few millimetres. To ensure that even this narrow anode-grid space is completely shielded from the electrons emitted from the cathode, except in the direction at right angles to the grid surface, two glass tubes T_1 and T_2 are provided as shown. The whole is supported from, and surrounded by a metal envelope *E*, whilst a cooling coil *CC* is provided to regulate the vapour-pressure to the correct operating value. The characteristic feature of such an amplifying valve is its high mutual conductance combined with low internal impedance. The former attains as much as 500 mA per volt, whilst the latter amounts to only 50 ohms in the case of the valves developed by Lübcke, which are rated to carry 5 A at 220 volts.

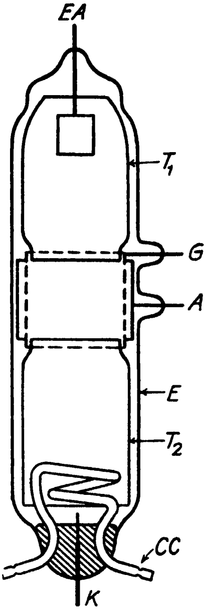

FIG. 159. CROSS-SECTION OF IONIC AMPLIFIER
Siemens & Halske A.G.

The Screened-grid Controlled Rectifier. In discussing the operation of vapour-arc discharge devices, such as the mercury-arc rectifier or the hot-cathode rectifier, it has been assumed until very recently that a grid located in the discharge path can exercise one controlling function only, viz. the initiation of the arc discharge; and that, once established, such a discharge can be extinguished only by an alteration of the electrical conditions which render it self-supporting. All practical applications of grid-controlled arc-discharge devices, therefore, have relied hitherto upon natural means, e.g. reversal of the electrode polarity, to provide the requisite extinction of the current arc. There can be no doubt that the inability of the control grid to perform this essential function has in many ways been an impediment to the technical fulfilment of certain current-convertor applications, and to the commercial development of others. For example, it has not been found possible to invert direct to alternating current unless either electromotive forces of fixed frequency or special commutating condensers be provided on the alternating-current side of the apparatus, to ensure that the anode voltages periodically pass through zero. Again, voltage control of the mercury-arc rectifier by means of grid excitation has laboured under the disadvantage of a deterioration of the power factor proportional to the reduction in output voltage.

These fundamental drawbacks to grid control as hitherto applied can be overcome at once if means are available for interrupting the anode current by direct arc control at the appropriate moment. And it must be regarded as a triumph of electro-physical science that it has at last been found possible to extinguish a current arc through the medium of a control grid situated in the discharge path.

In a paper read before the Swiss Association of Electrical Engineers early in 1933,* Kobel has demonstrated beyond doubt the fact that both continuous as well as alternating-current arcs can, under certain circumstances, be extinguished with certainty by grid control. As is to be expected, the conditions under which this is possible are similar to those obtaining in the ionic amplifiers developed by Lübcke and discussed in the preceding section. Kobel also employed a close-mesh grid immediately adjacent to the anode, but he has obtained completely different operating characteristics which make this new development of far-reaching importance. It has been explained in the case of the ionic amplifier that the anode current is carried entirely by electrons, as ionization of the vapour in the anode-grid space is completely prevented.* As the result the internal resistance is high, so that the voltage drop across the valve is considerable. In the case of a 5-A valve having a resistance of 50 ohms, the voltage drop will amount to 250 volts at full load. This is a serious disadvantage to be reckoned with in considering the practical applications of such a device.

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* E. Kobel: "The Interruption of an Anode Current by means of a Grid as applied to the Mercury-Arc Rectifier or Invertor," *Bulletin des Schweizerischer Elektrotechnische Vereins*, 1933, Vol. 24, pp. 41–48.

According to the Langmuir-Schottky space-charge law, the current density in an electron stream is given by $i = k \,.\, V^{\frac{3}{2}}/d^2$, where k is a constant ($2{\cdot}33 \times 10^{-6}$ for a pure electron current) and V is the voltage drop between two electrodes spaced d centimetres apart. Assuming a permissible drop of 20 volts between anode and grid of an ionic amplifier in which the anode-grid spacing reached 5 mm., this would give a valve current of only 0·25 A with an anode surface-area of 300 sq. cm. To obtain a current density of 3 A per sq. cm., as is usual in mercury-arc rectifiers, the anode-grid spacing would have to be less than one-tenth of a millimetre, which it is, of course, quite impossible in practice to obtain. Otherwise, with a separation between grid and anode of 5 mm., the voltage drop would reach close on 5 000 volts. As Kobel has pointed out, it is essential to the attainment of a reasonable anode-grid spacing, together with a sufficiently high current density, for positive ions to be present in order to neutralize the negative space-charge between anode and grid.

In spite of the fact that in the ionic amplifier no ionization by collision can take place in this region, positive ions tend to accumulate there as the result of gradual diffusion out of the cathode-grid space; and it is entirely due to the presence of these positive ions that the resistance of the anode-grid path attained a value not of some 7 000 ohms, as given by the above space-charge law, but only of 120 ohms in the particular case investigated by Kobel.† To reduce this resistance to a fraction of an ohm—a figure comparable to that obtaining in the case of the self-supported arc discharge—it becomes necessary to increase the vapour pressure. Only by thus diminishing the mean free path of the electrons is it possible to provide the requisite degree of ionization. The effect of vapour pressure on the processes of ignition and extinction of a direct-current arc by means of an alternating grid voltage is shown by the oscillograms of Fig. 160. Oscillogram (*a*) refers to a vapour pressure of 2 microns, and it is seen that the critical grid potential was as high as 115 volts. On the other hand, the negative potential required to produce extinction of the arc amounts to only a few volts. In the case of oscillogram (*b*), relating to a vapour pressure of 10 microns, it is evident that the arc is established immediately the grid becomes positive, whilst a negative potential of from 60 to 85 volts is necessary to extinguish the arc.

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* It should be mentioned here that due to the use of a mercury cathode and "cathode-spot" electron emission the quantity of electrons reaching the anode in a given time is very much greater than in the case of the vacuum valve, which can only rely upon thermionic emission. The ionic amplifier can consequently handle much heavier currents than the electronic amplifier.

† *Loc. cit.*, p. 44.

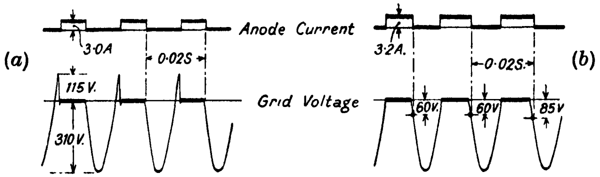

FIG. 160. INTERRUPTION OF A CONTINUOUS ANODE CURRENT BY MEANS OF AN ALTERNATING GRID VOLTAGE

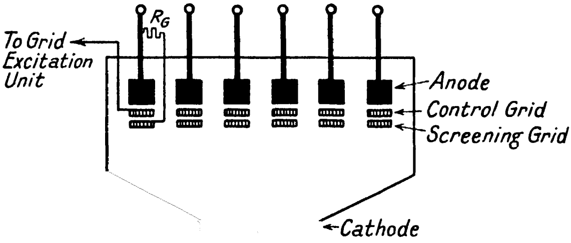

FIG. 161. ARRANGEMENT OF ANODE WITH CONTROL GRID AND SCREENING GRID

As the result of further investigation of the conditions governing extinction of the arc, Kobel has developed what may be termed a *screened-grid controlled rectifier*, by analogy with the screened-grid valve employed in wireless technique. The arrangement of the anode-grid structure is shown diagrammatically in Fig. 161. The screening grid is connected to

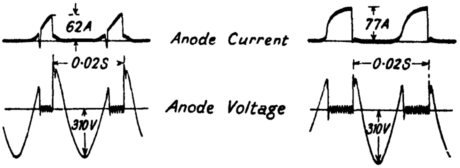

FIG. 162. INTERRUPTION OF AN ALTERNATING ANODE CURRENT BY MEANS OF SCREEN-GRID CONTROL

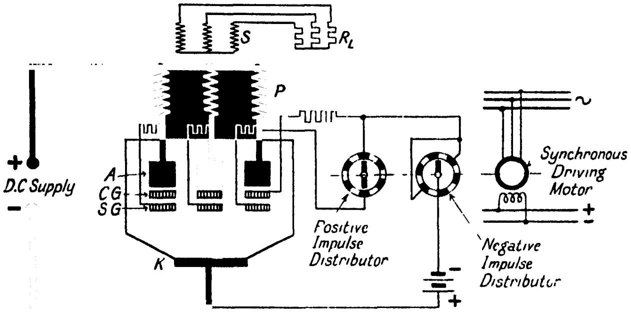
S
R_L
P
+
D.C Supply
−
A
CG
SG
K
~
Synchronous Driving Motor
+
−
Positive Impulse Distributor
Negative Impulse Distributor
−
+

FIG. 163. CONTROL CIRCUITS FOR INVERTOR UNIT WITH SCREEN-GRID CONTROL

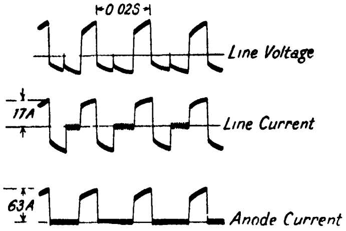

FIG. 164. SELF-DETERMINED INVERTOR OPERATION BY MEANS OF SCREEN-GRID CONTROL

the anode through a current-limiting resistance R_G, and its potential consequently follows that of the anode. The control grid proper is placed between the screening grid and the anode, close to the latter. The function of the screening grid is two-fold. In the first place it provides the ionization necessary for the initiation of the arc discharge, since it attracts the electron stream which then penetrates to the inter-grid space; and, secondly, it acts as a discharge path for the excess voltage generated in the instant of arc extinction.

Fig. 162 illustrates the extinguishing of a single-phase alternating-current arc in a steel-tank rectifier of the screened-grid controlled type. The screen-grid current flowing during the beginning and the end of the permeable half-cycle is visible in the oscillograms as the gradual rise and falling-away of the anode-current wave, which would otherwise rise suddenly to its peak value on ignition and fall equally rapidly to zero value on extinction of the current arc.

Finally, Fig. 163 illustrates the circuit employed by Kobel* to obtain inversion of direct current to three-phase alternating current by means of the same rectifier. The output transformer was loaded by resistance only. The grid-excitation unit comprised a positive impulse distributor and a negative impulse distributor driven by a 50-cycle synchronous motor. The timing was adjusted so that the current-conducting period was one-third of a cycle. The resulting output current and voltage wave-forms are given in Fig. 164. Such a method of self-determined inversion can only be described as revolutionary, and its possibilities in connection with the transmission of power by means of high-tension direct current are evident.

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(3) E. Lübcke: *Elektrotechnische Zeitschrift*, 1931, Vol. 52, p. 1513.
(4) E. Kobel: *Bulletin des Schweizerische Elektrotechnische Vereins*, 1933, Vol. 24, p. 41.

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* *Ibid.*, p. 47.

CHAPTER XIV

THE GENERATION OF HARMONICS BY THE MERCURY-ARC RECTIFIER

THE mercury-arc rectifier is, in the last analysis, a switching apparatus or commutating device, pure and simple, and its loading of the alternating-current supply system is therefore discontinuous. In this respect it differs fundamentally from other forms of electrical load, such as the transformer or induction motor, or rotating converting plant, all of which draw an even and unbroken flow of power from the source of supply. As the result of the discontinuity in the loading of the alternating-current network, the current supplied to the rectifier is no longer sinusoidal.

The general forms and instantaneous values of the line currents in the case of different types of rectifier circuit have been dealt with in Chapters IV, V and VI, where it was shown how the currents on the input side of a rectifier obey certain laws which depend on the nature of the rectifier load. All such currents, however, conform to the general rule whereby their wave-form must be such that when "strung together" their net effect over a whole cycle of alternating voltage is the same as would be produced by a continuous current. The resulting discontinuities in wave-form cause the primary phase currents and line currents to become distorted from the sinusoidal form. The resulting wave-form may be looked upon as equivalent to a fundamental sine wave upon which is superimposed a number of harmonics of varying order, magnitude and phase relationship.

At the same time the output voltage of a mercury-arc rectifier is also discontinuous, the degree of distortion from the rectilinear form again depending upon the nature of the rectifier load. In this case also the wave-form of the actual voltage on the direct-current side may be represented as a continuous voltage of constant magnitude upon which is superimposed a variety of harmonic alternating voltages.

Harmonics in the Direct-current Supply. As was explained in Chapter III, in connection with Fig. 9, the output voltage of a rectifier oscillates about a mean value V_d. The amplitude of the oscillations depends on the amount of reactance in the rectifier circuit, the bulk of which is naturally located in the transformer. The frequency of the oscillations is determined by the periodicity of the alternating-current supply and by the number of rectifier phases. Analysis of the output voltage wave shows it to consist, as mentioned above, of alternating-current harmonics superimposed on a constant direct-current pressure. Referring to Fig. 9, the rectified voltage may be represented by the Fourier series

$$\begin{aligned}F(\theta) = A_0 &+ A_1 \cos p\theta + A_2 \cos 2p\theta + A_3 \cos 3p\theta \\ &+ \ . \ . \ . \ A_m \cos mp\theta + \ . \ . \ . + B_1 \sin p\theta \\ &+ B_2 \sin 2p\theta + B_3 \sin 3p\theta + . \ . \ . \ B_m \sin mp\theta \\ &+ . \ . \ .\end{aligned}$$

The constant term, A_0, here represents the mean output voltage V_d. The series may be evaluated in the usual way by

$$A_n = \frac{p}{\pi}\int_{-\pi/p}^{\pi/p} F(\theta) \cos n\theta \, d\theta$$

and

$$B_n = \frac{p}{\pi}\int_{-\pi/p}^{\pi/p} F(\theta) \sin n\theta \, d\theta$$

Here $n = mp$, where m is an integer, and $F(\theta) = E\sqrt{2} \, . \cos \theta$, so that

$$\begin{aligned}A_n &= \frac{E\sqrt{2} \, . \, p}{\pi}\int_{-\pi/p}^{\pi/p} \cos \theta \cos mp\theta \, d\theta \\ &= \frac{E\sqrt{2} \, . \, p}{\pi(n^2 - 1)}\left[2mp \sin m\pi \cos \frac{\pi}{p} - 2 \cos m\pi \sin \frac{\pi}{p}\right] \\ &= \frac{E\sqrt{2} \, . \, 2p}{\pi(n^2 - 1)}\left[\pm \sin \frac{\pi}{p}\right] = \pm \frac{2}{n^2 - 1} \, . \, E\sqrt{2}\frac{p}{\pi} \sin \frac{\pi}{p} \\ &= \pm \frac{2V_d}{n^2 - 1}\end{aligned}$$

Also

$$\begin{aligned}B_n &= \frac{E\sqrt{2} \, . \, p}{\pi}\int_{-\pi/p}^{+\pi/p} \cos \theta \sin mp\theta \, d\theta \\ &= 0\end{aligned}$$

The coefficient A_n thus gives the amplitude of the harmonic of frequency $n = mp$. The r.m.s. value of the nth harmonic is therefore

$$E_n = \frac{\sqrt{2}}{n^2 - 1} V_d \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (26)$$

Under certain circumstances these harmonics, which are always present on the direct-current side of a rectifier to a greater or lesser degree, may give rise to interference with communication circuits. And investigations have from time to time been carried out to ascertain the extent of such interference and to determine means for its elimination.* It is therefore important to note how the occurrence of harmonics in the rectified voltage is affected by the number of rectifier phases. Table III gives the r.m.s. values of the several harmonics at no load, expressed as percentages of the mean output voltage V_d.

TABLE III

Frequency of the Harmonic	Number of Rectifier Phases			
	2	3	6	12
$2f$ = 100 cycles	47·13	—	—	—
$3f$ = 150 cycles	—	17·7	—	—
$4f$ = 200 cycles	9·44	—	—	—
$6f$ = 300 cycles	4·05	4·05	4·05	—
$8f$ = 400 cycles	2·25	—	—	—
$9f$ = 450 cycles	—	1·77	—	—
$10f$ = 500 cycles	1·43	—	—	—
$12f$ = 600 cycles	0·99	0·99	0·99	0·99
$14f$ = 700 cycles	0·73	—	—	—
$15f$ = 750 cycles	—	0·63	—	—
$16f$ = 800 cycles	0·56	—	—	—
$18f$ = 900 cycles	0·44	0·44	0·44	—
$20f$ = 1 000 cycles	0·36	—	—	—
$21f$ = 1 050 cycles	—	0 32	—	—
$22f$ = 1 100 cycles	0·29	—	—	—
$24f$ = 1 200 cycles	0·25	0·25	0·25	0·25

In the first place it is seen that the output voltage ripple contains only harmonics having frequencies which are multiples of both the supply frequency and the number of rectifier phases. Thus if f denotes the periodicity of the alternating-current supply and p the number of rectifier phases, then the frequency of any harmonic is given by mpf, where m is an integer. Secondly, it is to be noted that the individual harmonics have certain definite values which are quite independent of the rectifier phase number—a fact which is explained by equation (26).

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* *Vide* "Experiences with Resonant Circuits for the Elimination of Harmonics in Rectifier Installations," *V.D.E. Fachberichte*, 1928, p. 36; also E.R.A. Report M/T.13: "Interference from Mercury-Arc Rectifiers and the Effect of Filter Circuits," published in 1932.

The corresponding harmonics in the output current depend on the nature of the direct-current load. In the case of a pure resistance load, the current harmonics are directly proportional to, and in phase with, their corresponding voltage harmonics. Any inductance in the load circuit on the one hand reduces the magnitude of any current harmonic and, on the other, gives rise to a displacement in phase with respect to the generating voltage harmonic. Both influences depend upon the ratio of resistance to reactance of the load circuit for the particular frequency concerned.* Perfect smoothing of the direct-current output is therefore only to be obtained with an infinitely large cathode choke.

Harmonics in the Alternating-current Supply. The rapidly increasing use of rectifiers in their normal form and the many new fields of application opened up by grid control render imperative a general inquiry not only into the nature of the harmonics drawn from the supply, but also into the effect on their magnitude and phase relationships of different transformer connections and of the number of rectifier phases.

When investigating the generation of alternating-current harmonics by the mercury-arc rectifier we may legitimately assume the supply voltage to be sinusoidal. If, in addition, we neglect the magnetizing current of the transformer as well as the effect of magnetic leakage, the problem reduces to a comparatively simple form. In dealing with this problem, however, it must be borne in mind that only the fundamental component of the alternating-current wave can, together with the sinusoidal e.m.f., carry active power. The harmonics in the line current therefore are of little influence on the efficiency of the rectifier unit, but produce an increase in the r.m.s. value of the current, resulting in additional losses which are manifested by a deterioration of the power factor. The degree of deterioration is conveniently expressed by a distortion factor, the significance of which will be discussed in a later section.

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* It is beyond the scope of the present work to deal with the many conditions affecting the relation between the current and voltage harmonics on the output side of the rectifier. The problem is treated in all its aspects by O. K. Marti and H. Winograd in Chapter V of their book: *Mercury-Arc Power Rectifiers* (McGraw-Hill Book Co., 1930), to which reference should be made by those desiring detailed information on the subject.

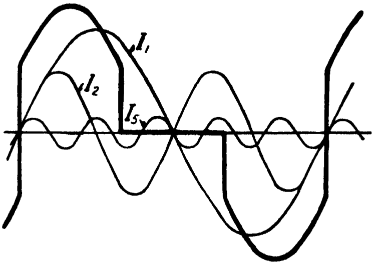


FIG. 165. LINE CURRENT OF THREE-PHASE RECTIFIER TRANSFORMER CONNECTION—GROUP I

$I = 0{\cdot}686 I_{max}$
$I_1 = 0{\cdot}576 I_{max}$

I.E.E. Journal

The deviation from the sinusoidal of the line current waveform depends largely on the transformer connection employed.

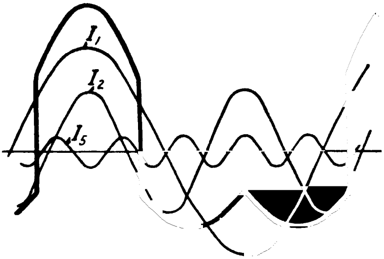


FIG. 166. LINE CURRENT OF THREE-PHASE RECTIFIER TRANSFORMER CONNECTION—GROUP II

$I = 0{\cdot}594 I_{max}$
$I_1 = 0{\cdot}499 I_{max}$

I.E.E. Journal

In the case of a three-phase rectifier supplying a non-inductive load, there are two forms of current wave (Figs. 165 and 166) corresponding to the following two groups of transformer connection—

Group I: Star/star; delta/interconnected-star.
Group II: Delta/star; star/interconnected-star.

Analysis of these two wave-forms shows the absence of triplen* harmonics and the presence of all other harmonics. Furthermore, the magnitudes of the various harmonics expressed as percentages of the fundamental are the same for both wave-forms. The latter differ only in the phase relationships of the harmonics to the fundamental, as may be seen by reference to Figs. 165 and 166.

The conditions are similar in the case of six-phase operation of the rectifier, in that here also the line current can have two different wave-forms. With six-phase rectifiers one has to distinguish between two fundamental types of transformer connection†—

(*a*) Six-phase connections *without* phase equalizing where the rectifier current is carried by one anode at a time, so that each secondary phase of the transformer in turn is loaded by the total direct current during one-sixth of the voltage cycle.

(*b*) Six-phase connections *with* phase equalizing where, by auxiliary means (e.g. interphase transformer, absorption reactance coil, or magnetic shunt), the rectifier current is delivered by two anodes simultaneously, so that each secondary phase of the transformer in turn is loaded by half the total direct current during one-third of the voltage cycle.

Taking this distinction into account we obtain the following two groups of connections corresponding to the wave-forms of line current shown in Figs. 167 and 168—

Group I: Delta/fork, without phase equalizing.
Delta/star, with phase equalizing.
Star/fork, with phase equalizing.‡

Group II: Delta/star, without phase equalizing.
Star/fork, without phase equalizing.
Star/star, with phase equalizing.
Delta/fork, with phase equalizing.

---

* The term "triplen" denotes frequencies which are multiples of 3.

† *Vide* Chapter V.

‡ Star/star connection of the transformer without phase equalizing, although strictly speaking belonging to Group I, has not been included as it leaves a residual m.m.f. of triplen frequency which is in phase on all three legs of the transformer core and which thus produces a triplen harmonic leakage flux. Beyond a certain load this leakage flux is sufficiently strong to induce phase-equalizing between pairs of anodes, when the connection functions as if belonging to Group II. In practice this connection is only employed with transformers in which the core is so arranged (e.g. shell type, 5-leg core type, or triple single-phase type of construction) that the leakage flux results in phase-equalizing at a very light load.

The analysis of the line current wave-forms of Figs. 167 and 168 indicates the absence of all even harmonics in addition to the triplen harmonics absent in Figs. 165 and 166. At first sight it would appear that the curve of Fig. 167 approaches more closely to the sine wave-form than that of Fig. 168. On investigation it will be found, however, that both curves contain the same harmonics. The difference in wave-form is accounted for by the fact that the corresponding harmonics in the two curves are of opposite sign.

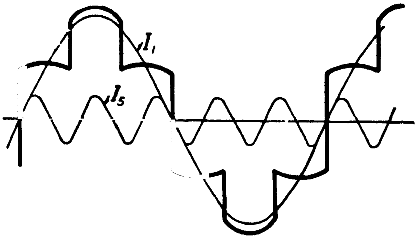


FIG. 167. LINE CURRENT OF SIX-PHASE RECTIFIER TRANSFORMER CONNECTION—GROUP I

$I = 0{\cdot}676 I_{max}$
$I_1 = 0{\cdot}646 I_{max}$

I.E.E. Journal

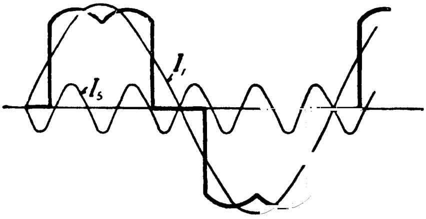


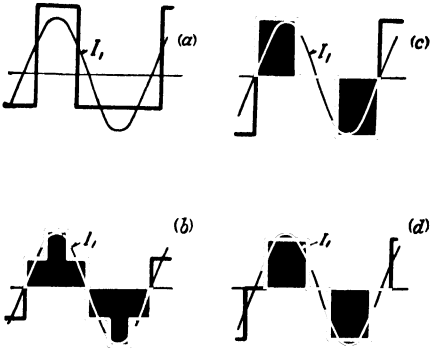
FIG. 168. LINE CURRENT OF SIX-PHASE RECTIFIER TRANSFORMER CONNECTION—GROUP II

$I = 0{\cdot}778 I_{max}$
$I_1 = 0{\cdot}745 I_{max}$

I.E.E. Journal

As is to be expected, analysis of the line current wave-form of twelve-phase rectifiers shows the absence of all even harmonics as well as those of triplen frequency. The residual current harmonics are of relatively small magnitude and hence the line current is practically sinusoidal. This feature, together with the small degree of ripple in the output voltage (*cf.* Table

III) renders the twelve-phase rectifier superior to the six-phase rectifier. It is for these reasons that attention is being paid more and more to the use of rectifier circuits having twelve-phase character, particularly so because such arrangements are at once cheaper and more efficient than the equivalent six-phase circuit in combination with smoothing equipment on the direct-current side. And where the cumulative effect of the harmonics taken by the rectifier from the alternating-current supply is likely to make itself felt, for example in the case of an extensive direct-current traction system fed solely from rectifier substations, it is clear that serious consideration must be given to twelve-phase working, in spite of the fact that the question of ripple in the output voltage may not be of such great importance.



Group I

Group II

FIG. 169. RECTIFIER LINE CURRENTS WITH PERFECT SMOOTHING OF THE DIRECT CURRENT

(a) and (c) three phases—

(a) $\begin{cases} I = 0{\cdot}707 I_{max} \\ I_1 = 0{\cdot}585 I_{max} \end{cases}$

(c) $\begin{cases} I = 0{\cdot}816 I_{max} \\ I_1 = 0{\cdot}675 I_{max} \end{cases}$

(b) and (d) six phases—

(b) $\begin{cases} I = 0{\cdot}707 I_{max} \\ I_1 = 0{\cdot}675 I_{max} \end{cases}$

(d) $\begin{cases} I = 0{\cdot}816 I_{max} \\ I_1 = 0{\cdot}778 I_{max} \end{cases}$

I.E.E. Journal

The Influence of Direct-current Smoothing Equipment. When investigating the effect which smoothing equipment on the direct-current side of the rectifier has upon the harmonics in the line current, it is convenient to consider the limiting case of the infinitely large cathode choke. In this case the primary currents are no longer composed of portions of sine waves, but are made up of individual rectangles as depicted in Fig. 169.

It is to be noted that both frequency and phase relationship of the alternating-current harmonics are unaffected by the smoothing reactor. The presence of inductance in the load circuit of the rectifier only affects the magnitude of the harmonics. Since the inductance is assumed infinite, the amplitudes of the individual harmonics are inversely proportional to their frequency. This relation considerably simplifies the investigation, as we can write

$$I_n = \frac{1}{n} I_1$$

where I_1 and I_n are the r.m.s. values of the fundamental and nth harmonic respectively. Table IV illustrates the effect of perfect smoothing of the direct current on the harmonics in the line current, the values of the individual harmonics being expressed as a percentage of the fundamental. In addition, the corresponding r.m.s. value of the total line current I is given at the head of each column.

Table IV indicates certain analogies with Table III as far as the influence of the number of rectifier phases is concerned. A particular harmonic on the direct-current side corresponds to two particular harmonics, the next lower and the next higher, on the alternating-current side. The twelfth harmonic in the direct current, for example, is always associated with the eleventh and thirteenth harmonics in the line current. The analogy becomes more evident when considering the parallel connection of rectifiers.

Parallel Connection of Rectifier Units. When operating rectifier units in parallel it is of importance to know the behaviour of harmonics in the direct-current system on the one hand, and in the alternating-current supply on the other. The relationship between these harmonics has just been indicated, and a practical illustration of the way in which their interdependence can be used to advantage should be noted. We shall consider two six-phase rectifier units, of equal output, operating in parallel on the direct-current side and taking power from a common alternating-current supply.

For the case in which the six-phase connections of the two units belong to the same group the harmonics generated by both rectifiers are individually in phase on the direct-current side as well as on the alternating-current side. As may be seen from Fig. 170 (*a*), the direct-current network has to carry

TABLE IV

Harmonic and Frequency	2 phases		3 phases		6 phases		12 phases	
	With d.c. Smoothing	Without d.c. Smoothing	With d.c. Smoothing	Without d.c. Smoothing	With d.c. Smoothing	Without d.c. Smoothing	With d.c. Smoothing	Without d.c. Smoothing
Resultant	111	100	121	119	104·5	105	101	101
Fundamental, 50 cycles	100	100	100	100	100	100	100	100
2nd Harmonic, 100 cycles	—	—	50·0	58·5	—	—	—	—
3rd Harmonic, 150 cycles	33·3	—	—	—	—	—	—	—
4th Harmonic, 200 cycles	—	—	25·0	14·6	—	—	—	—
5th Harmonic, 250 cycles	20·0	—	20·0	12·1	20·0	22·6	—	—
7th Harmonic, 350 cycles	14·3	—	14·3	8·6	14·3	11·3	—	—
8th Harmonic, 400 cycles	—	—	12·5	7·35	—	—	—	—
9th Harmonic, 450 cycles	11·1	—	—	—	—	—	—	—
10th Harmonic, 500 cycles	—	—	10·0	6·0	—	—	—	—
11th Harmonic, 550 cycles	9·1	—	9·1	5·5	9·1	9·1	9·1	9·1
13th Harmonic, 650 cycles	7·7	—	7·7	4·6	7·7	6·5	7·7	7·4
14th Harmonic, 750 cycles	—	—	7·1	4·3	—	—	—	—

a harmonic I_6 of six times the supply frequency, whilst the alternating-current network has to supply the corresponding harmonics I_5 and I_7 as is the case with normal six-phase working.

The conditions are, however, quite different where the six-phase connections of the two rectifier transformers belong to different groups. In this case (Fig. 170 (*b*)), the sixth harmonic in the output voltage of the one rectifier is in antiphase with the sixth direct-current harmonic of the other, so that a current I_6 of sextuple frequency circulates between the two units.

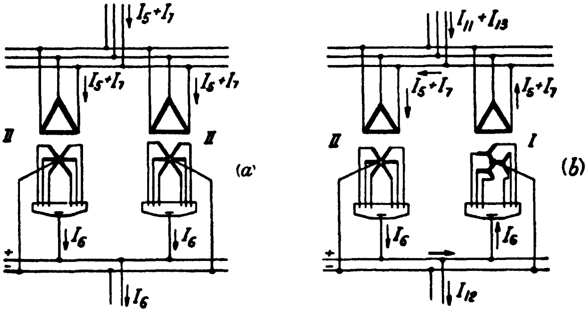


FIG. 170. PARALLEL CONNECTION OF SIX-PHASE RECTIFIERS
I.E.E. Journal

The direct-current network is thus not loaded by the sixth harmonic current, but carries instead the next higher harmonic —in this case the twelfth. As far as the direct-current supply is concerned, therefore, the two rectifiers operate as a twelve-phase unit for which the harmonic of maximum amplitude has a frequency twelve times that of the alternating-current supply. Similar conditions are encountered on the input side of the two units. Here the individual alternating-current harmonics supplied to each rectifier are also in antiphase, so that harmonic currents circulate between the two transformers. The first two harmonics corresponding to the sixth harmonic on the direct-current side are normally of quintuple and septuple frequency (I_5 and I_7 in Fig. 170 (*b*)). But since, in this case, these circulate throughout the primary windings of the two six-phase transformers, the first two harmonic currents to be drawn from the line are the two of next higher frequency, namely, I_{11} and I_{13}.

Thus we find that the harmonics appearing in both alternating-current and direct-current networks are those corresponding to twelve-phase working, in spite of the fact that both rectifier units have six-phase transformer connections. This arrangement of rectifiers in parallel is of particular interest where interference with communication circuits is anticipated, and this is to be avoided without having recourse to expensive smoothing equipment. For the practical application of this method it is a necessary condition that the rectifier units be adjacent as well as of equal output. If they are connected to bus-bar sections which are remote from one another, care must be taken to ensure that the harmonics of each six-phase system are in phase. This applies particularly to the direct-current side where the presence of smoothing reactors produces a displacement of the harmonics with respect to their phase position when smoothing equipment is absent. At the same time it is to be remembered that the twelve-phase system formed by two six-phase rectifier units operating in the above manner may have a tendency towards instability. Where rigid twelve-phase working is desired, it is necessary to make use of the "series" connection discussed at the end of Chapter VI.

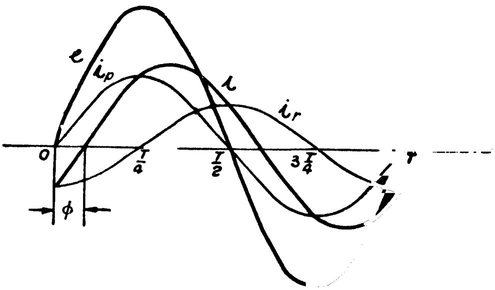


FIG. 171

$e = (E\sqrt{2}) \sin \omega t$ $i = (I\sqrt{2}) \sin (\omega t - \phi)$ $i_p = (I\sqrt{2}) \cos \phi \sin \omega t$

$i_r = -(I\sqrt{2}) \sin \phi \cos \omega t$ $T = 2\pi/\omega$

I.E.E. Journal

The Effect of Harmonics upon the Consumption of Apparent Power. In order to judge the effects of the harmonics generated by the mercury-arc rectifier upon the kVA loading which it imposes upon the supply system, it is necessary to consider the components of the apparent power in the case of non-sinusoidal voltage and current wave-forms. However, before investigating the mode of power production from alternating voltages and currents having quite a general wave-form, let us consider first of all the particular case where both voltage and current are sinusoidal, which, of course, represents the conditions obtaining in the majority of electrical machines.

Referring to Fig. 171, i is the sine wave of current flowing in a circuit and displaced by the phase angle ϕ with respect to the impressed e.m.f. e which is also sinusoidal. As is well known, the current can be resolved into two components, one of which, i_p, is in phase with the voltage, and the other, i_r, is in quadrature with the voltage. The former is known as the *power* component and the latter as the *quadrature* or *reactive** component. As may be seen from Fig. 172, the power component i_p produces, in combination with the voltage e, a power p which is strongly pulsating, but which nevertheless does not change its sign. This is known as the real or *active* component of the instantaneous power expressed by the product ei. Similarly, the quadrature component i_r combines with the voltage e to give a power p_r which is at times negative, at times positive. This component of the instantaneous power, called the *reactive* power, is expended in the circuit during the time intervals from $T/4$ to $T/2$, and from $3T/4$ to T. During the remaining time intervals, from 0 to $T/4$, and from $T/2$ to $3T/4$ this same power is given up by the circuit and returned to the supply.

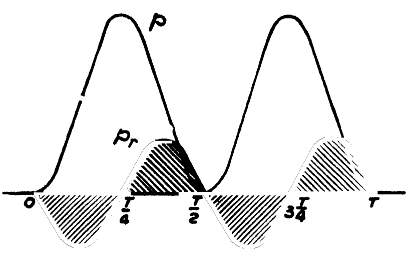


FIG. 172

$p = EI \cos\phi\,(1 - \cos 2\omega t)$
$p_r = -EI \sin\phi \sin 2\omega t$
$T = 2\pi/\omega$

I.E.E. Journal

The reactive power thus represents an idle product of current and voltage which is continually being pushed to and fro between the consumer and the supply, both of which have to be capable of dealing with it in addition to the useful power with which it is associated. In other words, the power flowing from the supply to the consumer oscillates between a lower and an upper limit. The mean value of the power represents that which can be transformed by the consumer into mechanical power. The amplitude of the oscillation represents the power for which both the consumer and the supply, as well as the electrical connections between them, have ultimately to be designed. The relation between these two is therefore a factor of importance in determining the degrees to which the generating plant and distribution system are ulitized by a consumer. This relation is generally expressed as the ratio of the active power to the total or apparent power in the circuit, and is then known as the *power factor*.

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* The general term *wattless* is purposely avoided here because, as will be shown later, it is not necessarily synonymous with the more specific term "reactive."

In the case illustrated in Figs. 171 and 172, the e.m.f. may be expressed by $e = (E\sqrt{2}) \sin (2\pi t/T)$ and the current by $i = (I\sqrt{2}) \sin (2\pi t/T - \phi)$, where E and I are the r.m.s. values. It can then readily be shown that the active power is given by $P = EI \cos \phi$, and the reactive power by $P_R = EI \sin \phi$. As the apparent power is $P_A = EI$, the power factor in this instance is $\lambda = \cos \phi$. Furthermore, $P_A{}^2 = P^2 + P_R{}^2$.

Turning now to the general case in which both voltage and current may be non-sinusoidal, the true or active power is still the mean value of the instantaneous power. But the latter oscillates in a most complicated manner which is quite different from that illustrated in Fig. 172 in connection with sinusoidal wave-forms. The oscillation can, however, be resolved into imaginary component oscillations by resolution of the current and voltage waves into their respective fundamental and harmonic sine waves. The instantaneous power then exhibits two kinds of oscillation. The first kind consists of products of currents and voltage having the same frequency, these oscillating powers having a frequency twice that of their respective constituent voltages and currents. The second kind comprises products of currents and voltages having different frequencies, and these power oscillations have a composite frequency.

Each oscillation of the first kind can be further split up into two component oscillations, as is the case with alternating currents and voltages of sinusoidal wave-form (Figs. 171 and 172). One of these is always of positive direction and fluctuates about a mean value $E_n I_n \cos \phi_n$, where E_n and I_n are the r.m.s. values of the nth harmonic in the voltage and current respectively, and ϕ_n is the phase displacement between these harmonics. This mean value represents the contribution of the harmonics to the active or useful power. The total active power is therefore

$$P = \Sigma E_n I_n \cos \phi_n \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

The other component continually changes its direction and oscillates about zero mean value. It represents the contribution of corresponding current and voltage harmonics to the reactive or idle power. The effective value of this component for the nth harmonic is $E_n I_n \sin \phi_n$, so that the total reactive power is

$$P_R = \Sigma E_n I_n \sin \phi_n \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

The power oscillations of the second kind, built up by the combination of currents and voltages of different frequency, also oscillate about zero mean value. Hence they do not contribute in any way towards the active power in the circuit. At the same time they do not contribute to the storage of magnetic or electrostatic energy and therefore do not add to the reactive power in the circuit. Such oscillations may arise in the case of a pure resistance load, a pure reactance load, or a combination of both. In all cases they constitute only an instantaneous excess of absorbed or released energy over that present in the circuit due to oscillations of the first kind. The power oscillations of the second kind therefore contribute to the product of the effective values of the voltage and current given by

$$E = \sqrt{[E_1^2 + E_2^2 + E_3^2 + \ . \ . \ . \ ]} = \sqrt{\Sigma E_n^2}$$

and

$$I = \sqrt{[I_1^2 + I_2^2 + I_3^2 + \ . \ . \ . \ ]} = \sqrt{\Sigma I_n^2}$$

In other words, the product $EI = P_A$, which is the total or apparent power in the circuit, is greater than the vector sum of the active and reactive powers by an amount equal to the sum total of all power oscillations of the second kind. To evaluate this latter quantity we have

$$\begin{aligned} P^2 + P_R^2 &= (\Sigma E_n I_n \cos \phi_n)^2 + (\Sigma E_n I_n \sin \phi_n)^2 \\ &= \Sigma E_n^2 I_n^2 \cos^2 \phi_n + \Sigma E_n^2 I_n^2 \sin^2 \phi_n \\ &\qquad + 2\Sigma E_m E_n I_m I_n \cos \phi_m \cos \phi_n \\ &\qquad + 2\Sigma E_m E_n I_m I_n \sin \phi_m \sin \phi_n \\ &= \Sigma E_n^2 I_n^2 + 2\Sigma E_m E_n I_m I_n \cos (\phi_m - \phi_n) \end{aligned}$$

$$= \Sigma E_n^2 \Sigma I_n^2 - \Sigma E_m^2 I_n^2 - \Sigma E_n^2 I_m^2 + 2\Sigma E_m E_n I_m I_n \cos(\phi_m - \phi_n)$$

$$= E^2 I^2 - \Sigma[E_m^2 I_n^2 + E_n^2 I_m^2 - 2E_m E_n I_m I_n \cos(\phi_m - \phi_n)]$$

Alternatively,

$$P_A - EI = \sqrt{}[P^2 + P_R^2 + \Sigma\{E_m^2 I_n^2 + E_n^2 I_m^2 - 2E_m E_n I_m I_n \cos(\phi_m - \phi_n)\}]$$

The apparent power P_A carried by a non-sinusoidal current in association with a non-sinusoidal voltage therefore has three distinct components. The first two components, viz. the active power P and the reactive power P_R, are those encountered in dealing with sinusoidal circuits, and then usually referred to as *power* and *wattless power* respectively. The third component is expressed by

$$P_H = \sqrt{}\Sigma[E_m^2 I_n^2 + E_n^2 I_m^2 - 2E_m E_n I_m I_n \cos(\phi_m - \phi_n)] \qquad (29)$$

which also has the dimensions of a power, as is to be expected. The author has defined this component as the *harmonic* power. Furthermore, in the author's opinion the general term wattless power should be applied to any oscillating power having zero mean value. Wattless power, so defined, then includes both reactive power and harmonic power. Moreover, the apparent power is then always the vector sum of the active power and the wattless power. By adopting these definitions confusion is avoided when translating ideas arrived at in considering the particular case of sinusoidal currents and voltages to the more general case where the currents and voltages have a wave-form which is not sinusoidal. Summing up, then, the following definitions of the several products of a current i and a voltage e apply, where

$$i = (\sqrt{2})\Sigma I_n \sin(n\omega t + \beta_n)$$

and $$e = (\sqrt{2})\Sigma E_n \sin(n\omega t + \alpha_n)$$

Active power,

$$P = \Sigma E_n I_n \cos\phi_n, \text{ where } \phi_n = \alpha_n - \beta_n;$$

Reactive power,

$$P_R = \Sigma E_n I_n \sin\phi_n;$$

Harmonic power,

$$P_H = \sqrt{\Sigma[E_m{}^2I_n{}^2 + E_n{}^2I_m{}^2 - 2E_mE_nI_mI_n\cos(\phi_m - \phi_n)]}$$

Wattless power,

$$P_W = \sqrt{[P_R{}^2 + P_H{}^2]}$$

Apparent power,

$$P_A = \sqrt{[P^2 + P_W{}^2]} = \sqrt{[P^2 + P_R{}^2 + P_H{}^2]}.$$

Harmonic Power and Distortion Factor. The following particular cases perhaps illustrate more clearly the peculiar nature of harmonic power. In the first place, if the phase displacement between current and voltage is the same for all harmonic frequencies, that is, if $\phi_m = \phi_n = \ldots$ etc., then equation (29) reduces to

$$P_H = \sqrt{\Sigma(E_mI_n - E_nI_m)^2} \quad . \quad . \quad . \quad . \quad (30)$$

If, moreover, the relation between current and voltage is the same for all frequencies, that is, if

$$I_m/E_m = I_n/E_n \ldots \text{etc.}$$

then the harmonic power becomes zero. These two conditions are only fulfilled simultaneously in the case of a circuit which contains resistance only, when $\phi_m = \phi_n = \ldots = 0$.

For a circuit containing only reactance

$$\phi_m = \phi_n = \ldots = \pm \tfrac{1}{2}\pi$$

the positive sign referring to capacitance and the negative sign to inductance. Furthermore, for the inductance

$$E_m/mI_m = E_n/nI_n = \ldots = \omega L$$

and for the capacitance

$$I_m/mE_m = I_n/mE_n = \ldots = \omega C$$

Also the contributions of the harmonics to the reactive power are in this case $P_{Rm} = \pm E_mI_m$, $P_{Rn} = \pm E_nI_n$, etc. Hence equation (30) for the harmonic power becomes

$$P_H = \sqrt{[\Sigma\{\sqrt{(m/n)} - \sqrt{(n/m)}\}^2P_{Rm}P_{Rn}]} \quad . \quad (31)$$

Whether any particular term

$$(p_h)_{m,n} = \{\sqrt{(m/n)} - \sqrt{(n/m)}\}\sqrt{[P_{Rm}P_{Rn}]}$$

of the harmonic power is positive or negative depends on the values accorded to m and n. However, for the same values of m and n it has the same sign for both inductive and capacitive cases. In other words, corresponding components of the harmonic power flowing in a condenser and in a choke coil are added arithmetically. On the other hand, corresponding components of the reactive power are added algebraically, since for any particular frequency these are of opposite sign.* There are therefore two reasons why it is impossible entirely to compensate the reactive power in a choke coil by connecting a condenser in parallel with it. In the first place, the resultant reactive power is zero for only one particular frequency. Secondly, the harmonic powers in the condenser and choke coil are additive. Hence the wattless power of the combination can only be made a minimum, but cannot be reduced to zero.

A further special case involving harmonic power which is of importance is that of the electric arc. As is well known, the current taken by an arc contains powerful harmonics even when the arc voltage is sinusoidal. The effective power in this case is the product of the sinusoidal voltage and the fundamental of the current wave, which is in phase with the sine wave of voltage. Thus $P = EI_1$ and $P_R = 0$. The wattless power is due entirely to the harmonics in the current wave and is given by

$$P_W = P_H = E\sqrt{[I_2^2 + I_3^2 + \ldots + I_n^2 + \ldots]} \quad . \quad (32)$$

The apparent power taken by the arc is therefore

$$P_A = \sqrt{[P^2 + P_W^2]} = E\sqrt{\Sigma I_n^2} = EI$$

where I is the r.m.s. value of the current.

A similar example is afforded by the iron-cored choke which, even under the influence of a sinusoidal e.m.f., takes a distorted magnetizing current. Here the effective power is $P = EI_1 \cos \phi_1$, and the reactive power $P_R = EI_1 \sin \phi_1$. The harmonics in the magnetizing current combine with the sinusoidal e.m.f. to give the harmonic power

$$P_H = E\sqrt{[I_3^2 + I_5^2 + I_7^2 + \ldots]} \quad . \quad . \quad (33)$$

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* Steinmetz held the opposite view, maintaining that only the absolute values of the reactive power components are to be considered, regardless of whether such components are due to leading or lagging current harmonics. Schenkel is of the same opinion where a determination of the reactive power consumption of mercury-arc rectifiers is concerned (see *Elektrotechnische Zeitschrift*, 1925, Vol. 46, p. 1400).

In general, then, harmonic power is present whenever the resultant current wave is distorted with regard to the voltage wave.

By introducing the conception of harmonic power it is possible when dealing with non-sinusoidal circuits to retain the meaning attaching to reactive power and apparent power in the case of sinusoidal circuits. At the same time its practical value is undoubtedly affected by the fact that the harmonic power cannot be determined directly, but only indirectly through harmonic analysis of oscillograms. The reactive power can also not be measured directly except in the one case—of great practical importance—where the voltage is sinusoidal. The value which is nowadays placed on the measurement of reactive power, whether directly by reactive-kVA meters or indirectly by power-factor meters, arises from the fact that reactive power increases the transmission losses and consequently leads to a deterioration in the utilization factor of generating and distributing plants.

As far as transmission losses are concerned, it is, however, immaterial whether these are due to the presence of reactance or of harmonics. The harmonic power, like the reactive power, contributes towards the system losses; and in the case of rectifiers this contribution is by no means inconsiderable. Schenkel* when publishing the results of some investigations into the measurement of the reactive power taken by mercury-arc rectifiers showed, for a six-phase rectifier, that the reactive power amounted to 56 per cent and the harmonic power to no less than 80 per cent of the active power. The vector sum of these two gives a wattless power approximately equal to the active power. This was, however, for a comparatively small unit. For a modern unit of large output the reactive power is about 30 per cent, and the harmonic power about 20 per cent of the active power of the rectifier, corresponding to a wattless power of 36 per cent and a power factor of 0·94.

The effect of harmonic power is generally taken into account by means of a ratio expressing the reduction in available kVA due to the presence of the harmonics. This ratio, known as the *distortion factor* μ, is defined by the equation

$$\mu = [\sqrt{(P_A^2 - P_H^2)}]/P_A \quad . \quad . \quad . \quad . \quad (34)$$

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* *Loc. cit.*

In the case of rectifier installations, where the supply voltage may legitimately be assumed to be sinusoidal, the distortion factor so defined becomes simply the ratio of the r.m.s. value of the fundamental component of the line current to that of the resultant current, including both fundamental and harmonic components.

The Power Factor of the Mercury-arc Rectifier. Power factor is commonly regarded as being a circuit phenomenon arising from phase displacement between alternating currents and voltages. This fundamentally incorrect view has arisen, more or less inevitably, from the study of electrical machines, such as alternators, transformers and induction motors, in which the deviation from the sine curve of both current and voltage wave-forms is so slight as to permit of its being neglected in practice. It is only since we have grown familiar with the electric discharge and its varied applications that we have been forced to realize that such a conception of power factor leads to erroneous and even impossible conclusions. In electric discharge devices, such as the mercury-arc rectifier, the neon tube, and the gas-discharge lamp—to mention but a few typical and well-known examples—we encounter for the first time apparatus in which the distinction between power factor and the cosine of an angle of phase displacement becomes clearly apparent. This is accounted for by the fact that the traces of current and voltage no longer exhibit a wave-form which is truly sinusoidal.*

To obtain a clear understanding of its meaning as applied to non-sinusoidal alternating-current circuits, it must be remembered that power factor is essentially a numerical ratio expressing efficiency of power utilization. The smaller its value, the less is the useful power in proportion to the total power available. The power factor of a consumer is defined, therefore, as the ratio of the power usefully consumed (watts or kW) to the apparent power supplied (voltamperes or kVA).

Considering an instantaneous current i of r.m.s. value I, in conjunction with an instantaneous voltage e, having an r.m.s.

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* Here again it is beyond the scope of the present work to consider the general case of power factor in alternating-current circuits. References to the available bibliography on this complex problem will be found in a paper by the author published in the *I.E.E. Journal,* 1933, Vol. 72, p. 435. An outline of the problem has been given by the author in an article which appeared in the *Electrical Times* on the 6th April, 1933.

value E, then if the active power carried by the current be P, the power factor is thus defined by

$$\lambda = P/IE$$

which is a function of the load. Then it is true that

(1) $\lambda \leqq 1$ and is only equal to unity if e and i have the same form, i.e. if $e/i =$ a constant.

(2) Only when e and i are sinusoidal is $\lambda = \cos \phi$, where ϕ represents the phase displacement between e and i. If this phase displacement be indicated by $\lambda(\phi)$, then we have $\lambda(0) = 1$.

(3) If e be sinusoidal and i non-sinusoidal but symmetrical, then λ can be represented by

$$\lambda(\phi) = \lambda(0) \cos \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

where ϕ is also a phase displacement. Here $\lambda(0)$ represents the value of $\lambda(\phi)$ at no load.

In case (2) the power factor λ is a universal characteristic by which the degree and manner in which the generating plant is stressed by the power consumer may be determined. The electrical stressing is indicated by

$$P_A = P/\cos \phi = P/\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

At the same time λ is a measure of the magnetic stressing of the generating plant as expressed by the reactive power

$$P_R = P_A \sin \phi = P_A \sqrt{[1 - \lambda^2]} \quad . \quad . \quad . \quad (37)$$

In case (3), with which we are here concerned, however, the power factor can no longer determine the magnetic stresses, although it is by definition still a measure of the electrical stresses imposed on the generating plant. This is apparent from a consideration of the equation

$$P_A{}^2 = P^2 + P_R{}^2 + P_H{}^2 = P^2 + P_W$$

which, for $P = \lambda P_A$, gives

$$P_W = P_A \sqrt{[1 - \lambda^2]} \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

which is not the same result as (37). However, if we write

$$P_R = P_A \sqrt{[1 - \lambda_R{}^2]} \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

we obtain a "reactive" power factor λ_R which can be used to determine the reactive power (kVAR) loading.*

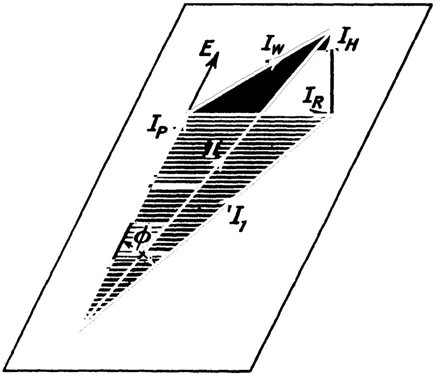

FIG. 173. COMPONENTS OF A NON-SINUSOIDAL ALTERNATING CURRENT

In the case of the mercury-arc rectifier, where the line voltage may be assumed sinusoidal, the problem of determining the power factor is simplified in that it permits of both a physical interpretation and a graphical solution. We may write for the line voltage

$$e = (E\sqrt{2}) \sin \omega t.$$

The non-sinusoidal line current may be represented by the Fourier series

$$i = \Sigma(I_n\sqrt{2}) \sin (n\omega t - \phi_n)$$

giving an r.m.s. value

$$I = \sqrt{\Sigma I_n^2} = \sqrt{(I_1^2 + I_2^2 + I_3^2 + \ldots)}$$
$$= \sqrt{(I_1^2 + I_H^2)}$$

where I_1 is the r.m.s. value of the fundamental component and I_H that of all the harmonic components. The fundamental, being a sinusoidal current, may be resolved into its two components as shown in Fig. 171. One is the active or power component $I_P = I_1 \cos \phi$; whilst the other is the reactive or quadrature component $I_R = I_1 \sin \phi$. We then obtain the relation

$$I^2 = I_P^2 + I_R^2 + I_H^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

illustrated vectorially in Fig. 173. The fundamental and its two components all lie in the sinusoidal plane (shown shaded). The active component I_P is in phase with the line voltage E, the reactive component I_R lags 90 electrical degrees behind the voltage, whilst the fundamental I_1 lags behind E by the phase angle ϕ. The harmonic component I_H is at right angles to the sinusoidal plane. On multiplying equation (40) throughout by

---

* From equations (38) and (39) we obtain

$$P_H = \sqrt{(P_W^2 - P_R^2)} = P_A\sqrt{[\lambda_R^2 - \lambda^2]}$$

whilst from equation (34) we find for the distortion factor

$$\mu = \sqrt{[1 - (\lambda_R^2 - \lambda)^2]}$$

Consequently $$P_H = P_A\sqrt{[1 - \mu^2]}$$

so that the distortion factor may, in the same way, be looked upon as a "harmonic" power factor, by means of which the harmonic power loading may be determined.

$3E^2$ we obtain the corresponding power relation

$$P_A^2 = P^2 + P_R^2 + P_H^2 \quad . \quad . \quad . \quad . \quad . \quad (40a)$$

in which $P_A = (\sqrt{3})EI$ is the total or apparent power, i.e. the line kVA; $P = (\sqrt{3})EI_1 \cos \phi$ is the useful or active power; $P_R = (\sqrt{3})EI_1 \sin \phi$ is the reactive power; and $P_H = (\sqrt{3})E \,.\, \sqrt{(I_2^2 + I_3^2 + \ldots + I_n^2 + \ldots)}$ is the harmonic power. The wattless power,* defined as the vector sum of the reactive and harmonic powers, is in this case

$$\begin{aligned} P_W &= (\sqrt{3})EI_w \\ &= (\sqrt{3})E \,.\, \sqrt{(I_1^2 \sin^2 \phi + I_2^2 + I_3^2 + \ldots} \\ &\quad \overline{+ I_n^2 + \ldots)} \end{aligned}$$

The power factor of the rectifier is thus

$$\lambda = P/P_A = I_1 \cos \phi/I \quad . \quad . \quad . \quad . \quad . \quad (41)$$

The distortion factor is, similarly,

$$\mu = [\sqrt{(P_A^2 - P_H^2)}]/P_A = [\sqrt{(I^2 - I_H^2)}]/I = I_1/I \quad (42)$$

Hence the rectifier power factor is given finally by

$$\lambda = \mu \,.\, \cos \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

In this equation $\cos \phi$ is the cosine of the phase angle between the voltage and the fundamental component of the current, and is termed the *displacement factor*. The reactive power factor λ_R giving a measure for the reactive power consumption of the rectifier is found from equation (39) to be

$$\begin{aligned} \lambda_R &= [\sqrt{(P_A^2 - P_R^2)}]/P_A = [\sqrt{(I^2 - I_1^2 \sin^2 \phi)}]/I \\ &= \sqrt{(1 - \mu^2 \,.\, \sin^2 \phi)} \quad . \quad . \quad . \quad . \quad . \quad (44) \end{aligned}$$

Equation (44) may be written in the form

$$\lambda_R = \delta \,.\, \cos \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

where

$$\delta = \sqrt{[1 + (1 - \mu^2) \tan^2 \phi]},$$

from which it is at once seen that the reactive power factor λ_R is for all practical purposes identical with the displacement factor $\cos \phi$. For example, the value of δ for a six-phase rectifier at full load, taking into account the magnetizing current of the transformer, is 1·002 approximately. In any case, by putting $\lambda_R = \cos\phi$ the error is on the correct side, since the value of P_R given by $P_A \sin\phi$ is actually somewhat greater than the true value given by $P_A\sqrt{[1 - \lambda_R^2]}$.

---

* *Cf. Electrical Review*, 1933, Vol. 112, p. 383.

Both the power factor and the displacement factor can be determined by means of wattmeters, voltmeter, and ammeter. For we have, by definition,

$$\lambda = \frac{P}{EI} = \frac{\text{watts}}{\text{volts} \times \text{amperes}}$$

Furthermore, by the two-wattmeter method we obtain

$$W_1 = kEI\mu \cos(\tfrac{1}{6}\pi - \phi)$$

and

$$W_2 = kEI\mu \cos(\tfrac{1}{6}\pi + \phi)$$

giving

$$\tan\phi = \sqrt{3}\,.\left(\frac{W_1 - W_2}{W_1 + W_2}\right)$$

from which $\lambda_R = \cos\phi$ can be determined. The distortion factor is then finally given by $\mu = \lambda/\cos\phi$.

In the mercury-arc rectifier the occurrence of an angle of phase displacement between current and voltage is due to the overlapping of the individual anode currents which, in turn, is occasioned by the presence of reactance in the rectifier transformer as explained in Chapter III. In this case the delay in arc commutation, expressed by the angle of overlap u, occurs quite naturally and is, moreover, a function of the load on the rectifier. It is to be expected, therefore, that the phase displacement between primary current and phase voltage (or line current and phase-to-neutral voltage) should bear some definite relation to the angle of overlap, and that the displacement factor of the rectifier should consequently vary with the load also. That this is actually the case may be seen by reference to Fig. 174. Diagrams (*a*) and (*b*) show the output voltage and anode current wave-forms in the case of a single-phase full wave rectifier. Diagram (*c*) illustrates the relation of primary current to primary phase voltage on the assumption that the current wave-form is rectangular, i.e. neglecting the effect of transformer reactance in tending to diminish the rate of rise and fall of the current at the beginning and end of each half wave.

The reactance voltages are indicated by the shaded areas in Fig. 174 (*a*). The reactive powers produced by these voltages in association with the rectifier current must be zero taken over the whole cycle as, by definition, the mean value of any wattless power is zero. Consequently the product of current and voltage during the period from ϕ to u at the beginning of the positive half cycle, must be equal and opposite to the same product taken over the period from zero to ϕ at the beginning

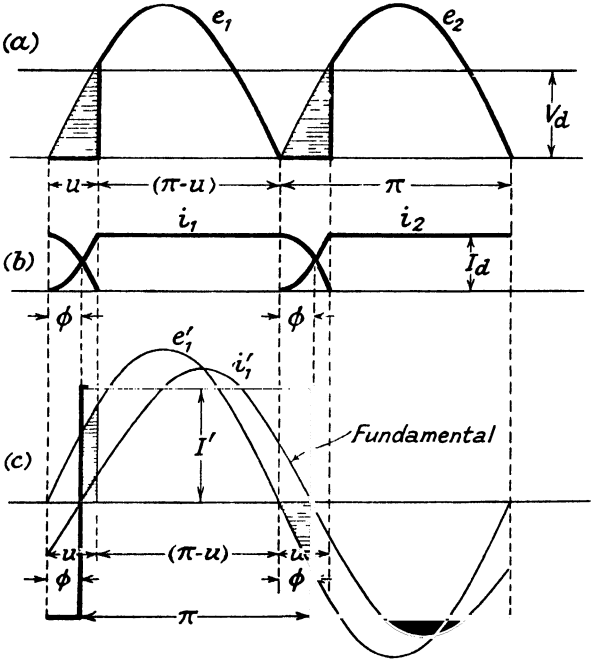

FIG. 174. PHASE DISPLACEMENT DUE TO OVERLAP
(a) Rectified voltage (b) Anode current (c) Primary current

of the negative half cycle. Hence we obtain from Fig. 174 (c) the condition that,

$$\int_{\phi}^{u} I'E'\sqrt{2} \, . \sin x \, dx + \int_{\pi}^{\pi+\phi} I'E'\sqrt{2} \, . \sin x \, dx = 0$$

i.e. that

$$[\cos \phi - \cos u] + [\cos \pi - \cos (\pi + \phi)] = 0,$$

which gives

$$\cos \phi = (1 + \cos u)/2 = \cos^2(u/2) \tag{46}$$

But from equation (4*a*) we have

$$\cos^2 (u/2) = V_d/V_{d_0}$$

so that, finally, we arrive at the relation

$$\cos \phi = V_d/V_{d_0} \qquad . \qquad . \qquad (47)$$

This fundamental relation is of considerable importance and may be stated in quite general terms, as follows: *If the ohmic losses in the rectifier and its associated transformer are neglected, then the displacement factor is given by the ratio of the mean output voltage at full load to that at no load.*

The distortion factor is, similarly, a function of the rectifier load. At no load, when $u = 0$, the anode currents have a rectangular wave-form and the line currents consequently take on the outlines illustrated in Fig. 169. The no-load values of the distortion factor for different numbers of rectifier phases may therefore be taken from Table IV, remembering that $\mu = I_1/I$. These values are as follows

p:	2	3	6	12
μ_0:	0·9	0·826	0·955	0·988

The effect of transformer reactance is not only a displacement of the primary current wave, but also an alteration in the overlapping of the anode currents, and therewith a change in the distortion of the primary current as compared with that obtaining at no load. As already mentioned, both these changes are dependent on the rectifier load, as this determines the amount of overlap for a given transformer reactance. An increase in load results on the one hand in a reduction of the relative distortion and, on the other, in an increase in the displacement of the current with respect to the voltage. In other words, with rising load the distortion factor increases, whilst simultaneously the displacement factor decreases—the latter effect eventually preponderating beyond 25 to 50 per cent overload in the case of rectifier units with transformers of normal reactance value. The increase of the distortion factor with load is proportional to the reduction in r.m.s. value of the anode currents and is thus determined by the factor

$\sqrt{[1 - p \cdot \psi(u)]}$ of Fig. 14. The distortion factor at any given load may thus be obtained from the relation

$$\mu = \mu_0/\sqrt{[1 - p \cdot \psi(u)]} \quad . \quad . \quad . \quad (48)$$

Fig. 175 shows the variation of cos ϕ, μ, and λ with load, as expressed by cos u, for the case of double three-phase rectifier operation of a six-phase rectifier, and is typical of the relation

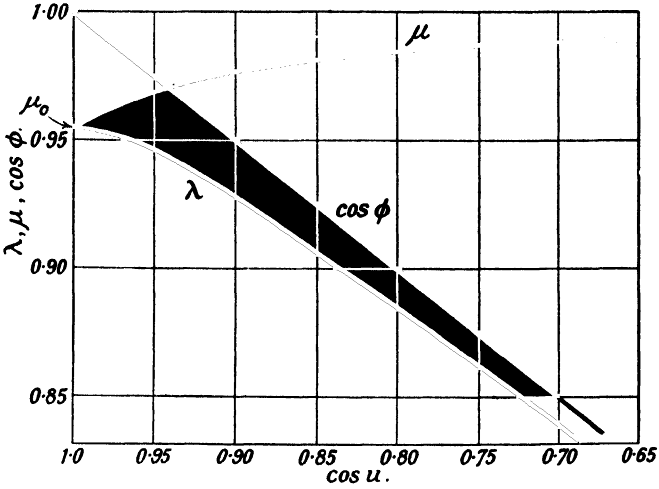

FIG. 175. VARIATION OF DISTORTION FACTOR, DISPLACEMENT FACTOR AND POWER FACTOR WITH THE ANGLE OF OVERLAP

between these several circuit quantities and the overlapping of the anode currents.

The Influence of Grid Control upon Power Factor and Harmonic Generation. The fact that grid control provides a means of voltage control through the medium of *artificially delayed* arc commutation, i.e. quite independently of the natural delay due to overlapping of the anode currents, immediately raises the question of the effect of such grid control upon the power factor of the rectifier. Referring to diagram (*a*) of Fig. 176, the loss in available output voltage due to retarding the instant of arc commutation by the so called *ignition angle* α is indicated by the shaded areas; and as was shown in Chapter X, there is a definite relation between the mean output voltage V_d and the angle α. According to equation (25), this relation is

$$\cos\alpha = V_d/V_{d_0} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (49)$$

where V_{d_0} is the maximum value of V_d, at no load and with $\alpha = 0$.

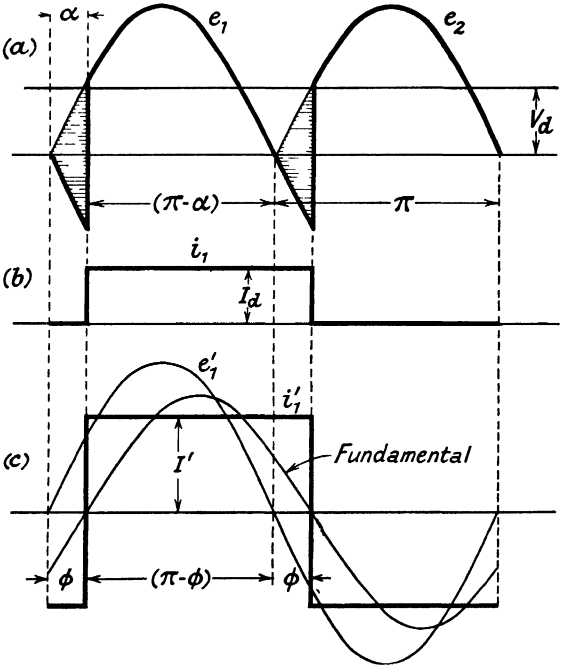

FIG. 176. PHASE DISPLACEMENT DUE TO GRID CONTROL

(*a*) Rectified voltage (*b*) Anode current (*c*) Primary current

Now in the case of a rectifier, as with other forms of converting plant, if all losses are neglected, then the power output on the direct-current side must be equal to the *active* power input on the alternating-current side. Consequently we obtain the power equation

(Output kW) = (Input kVA) × (Power Factor)

or,

$$V_d \cdot I_d = W_L \times \mu_0 \cos\phi \quad . \quad . \quad . \qquad (50)$$

The distortion factor μ_0, being the ratio of the r.m.s. fundamental component of the line current to the total r.m.s. line current is given by the ratio of W_d, the apparent direct-current kW output at the secondary terminals of the rectifier transformer (i.e. the kW output of the rectifier on the assumption that no drop in the mean output voltage takes place), to W_L, the apparent kVA in the line.* Hence

$$W_L = W_d/\mu_0 = (V_{d_0}.I_d)/\mu_0$$

so that equation (50) reduces to

$$V_d = V_{d_0} . \cos\phi \quad . \quad . \quad . \quad . \quad . \quad (51)$$

Comparing this equation with equation (49), we arrive at the important conclusion that $\cos\phi = \cos\alpha$. In other words: *If the power losses in a grid-controlled rectifier and its associated transformer are neglected, then the displacement factor is numerically equal to the cosine of the ignition angle.*

Again, on comparing equations (47) and (51), it is seen that in the case of grid-controlled rectifiers also the displacement factor is directly proportional to the mean output voltage.

On referring to Fig. 176 the reason is at once apparent. Due to grid-control the anode current i_1 lags the anode voltage e_1 by the ignition angle α. As the result, the corresponding primary current i_1' also lags behind the primary phase voltage e_1' by the same angle. Neglecting the effect of overlap, discussed in the preceding section, it is seen from diagram (*c*) that the phase displacement ϕ of the fundamental component of primary current is identical with the ignition angle α. If the effect of overlap be taken into account, the total primary phase-displacement is then equal to the sum of the individual displacements due to grid-control and overlap, i.e. $\phi = (\alpha + u)$. In other words, the relation $\cos\phi = V_d/V_{d_0}$ holds good in all cases, quite irrespective of the fact that the reduction in terminal voltage may be due either to grid-control or to transformer reactance. This universal relationship may be stated as follows: *In a mercury-arc rectifier the reduction in displacement factor is directly proportional to the reduction in the direct-current terminal voltage.*

The influence of grid-control upon the power factor of a typical six-phase rectifier unit is illustrated by Figs. 177, 178, 179, and 180. Diagram (*a*) of Fig. 177 shows the output voltage, whilst diagram (*b*) depicts the formation of the output current

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* *Cf.* Tables II and IV.

I_d, in the case of $\alpha = 0°$ and $V_d = V_{d_0}$. Diagram (*c*) shows the corresponding line current I_L, which is in phase with the phase-to-neutral voltage E_L as the effect of overlap has been neglected for the sake of clarity. The current distortion introduced into the supply network due to the non-sinusoidal wave-form of the line current is clearly illustrated by Fig. 178. In this case not only the fundamental but also the harmonic components of the line current I_L are in phase with the voltage E_L.

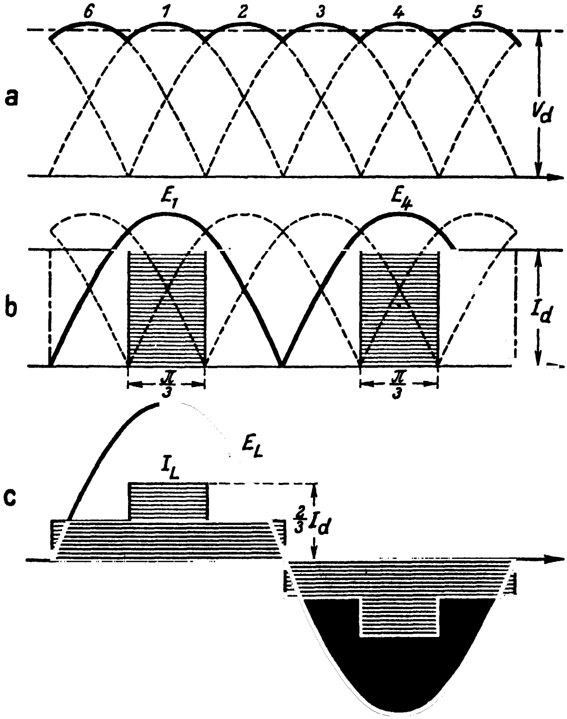

FIG. 177. CURRENT AND VOLTAGE RELATIONS WITH $\alpha = 0°$ AND PERFECT SMOOTHING OF THE DIRECT CURRENT

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Fig. 179, by comparison with Fig. 177, shows the effect of retarding the instant of arc ignition by the angle $\alpha = 60°$. The mean output voltage V_d is halved, whilst the anodes carry the load current I_d one-sixth of a cycle later. As the result, the line current I_L lags behind its corresponding voltage E_L by

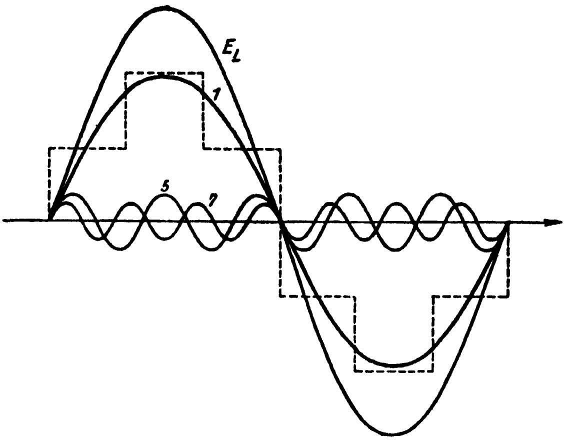

Fig. 178. Resolution of the Line Current into its Fundamental and Harmonic Components (See Fig. 177)

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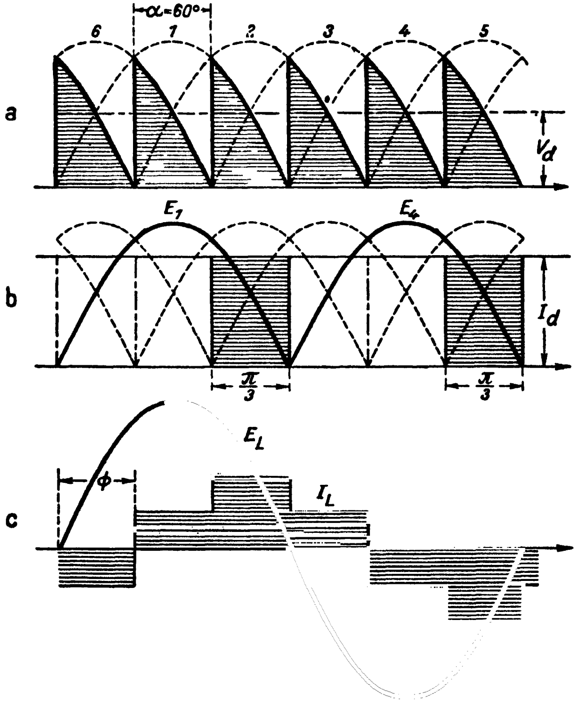

Fig. 179. Current and Voltage Relations with $\alpha = 60°$ and Perfect Smoothing of the Direct Current

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the phase angle $\phi = 60°$. At the same time the current distortion is unaltered,* as may be seen by comparison of Fig. 180 with Fig. 178. In this case both the fundamental and the harmonic components of the line current are displaced in phase with respect to the voltage E. The fundamental I_1 is in turn shown resolved into its two components; the power or active component $I_P = I_1 \cos \phi$ in phase with the voltage E, and the quadrature or reactive component $I_R = I_1 \sin \phi$, 90° out of phase with E. It is clear, therefore, that with the retardation of the instant of arc ignition by grid-control is associated a very marked consumption of reactive power. In fact, the reactive power loading of a grid-controlled rectifier increases rapidly as the output voltage is reduced, the relation being expressed by

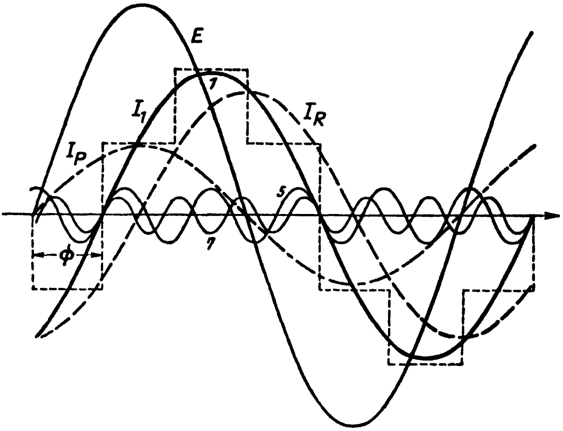

FIG. 180. RESOLUTION OF THE LINE CURRENT INTO ITS ACTIVE, REACTIVE, AND HARMONIC COMPONENTS (See Fig. 179)

$$P_R = P_A\sqrt{[1 - (V_d/V_{d_0})^2]} \quad . \quad . \quad . \quad . \quad (52)$$

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* Strictly speaking, this statement is only valid if the output current I_d is non-fluctuating at all values of rectifier load and ignition angle, that is, if the degree of smoothing on the direct-current side is considerable. The wave-form conditions on the alternating-current side will alter, however, if the degree of smoothing is inappreciable, i.e. if the rectifier load consists chiefly of resistance. Under these conditions an increase in the ignition angle α is accompanied not only by the phase displacement described above, but also by a variation in magnitude of the individual harmonics. As this case occurs only seldom in practice it will not be considered here.

In this respect, therefore, the grid-controlled rectifier differs materially from the normal type of rectifier, where the phase displacement seldom exceeds a maximum value of 25° to 30°, occurring at full load.

The connection between the several components of the line current and the ignition angle is represented graphically in

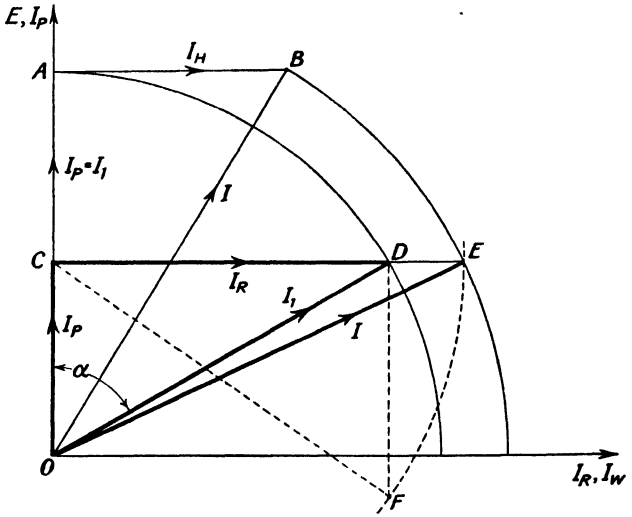

FIG. 181. RELATION BETWEEN IGNITION ANGLE AND COMPONENTS OF THE LINE CURRENT

$I_1/I = \mu$; $I_P/I_1 = \cos\phi$
$I_P/\text{I} = \mu\cos\phi = \lambda$
$I_R/I = \mu\sin\phi = \lambda\tan\phi$
$I_H/I = \sqrt{}(1-\mu^2)$; $I_W/I = \sqrt{}(1-\lambda^2)$

Fig. 181. By means of such a diagram it is a comparatively simple matter to evaluate the active power, reactive power, and harmonic power drawn by a rectifier from the alternating-current supply for different values of the mean output voltage as determined by the fundamental relation $V_d = V_{d_0} \,.\, \cos\alpha$. The phase-to-neutral voltage E and the power component I_P of the line current are taken as ordinates, whilst the reactive component I_R and the *wattless* component $I_W = \sqrt{}(I_R^2 + I_H^2)$ are taken as abscissae. At maximum output voltage ($\alpha = 0°$) I_P is represented by OA, and I_H by AB, so that OB then represents the line current I. The reactive component I_R is in this

case zero. With $\alpha = 60°$, for example, the output voltage is reduced by one-half, and I_P accordingly is represented by $OC = \frac{1}{2}(OA)$, since the direct-current output has been reduced in the same proportion. The reactive component $I_R = I_1 \sin \phi = I_1 \sin \alpha$ is then represented by CD. The vector sum of these two components, namely, OD, therefore represents the fundamental component I_1 of the line current, which has the same value as before, so that $OD = OA$. The line current I must also have the same value as before, since the fundamental and harmonic components are unaltered in value by any change in the ignition angle α. By making $DF = AB$ and drawing the arc FE about C as centre, we obtain $CE = CF = \sqrt{[(CD)^2 + (DF)^2]}$. Hence CE represents the wattless component I_W of the line current. Finally, OE represents the line current $I = \sqrt{(I_P{}^2 + I_W{}^2)}$.

The displacement factor $\cos \phi$ is given by the ratio OC/OD. The power factor λ is then given by the ratio OC/OE, whilst the distortion factor μ is similarly given by the ratio OD/OE.

Although any change in the ignition angle has, in general, no sensible effect upon the magnitude of the harmonics on the alternating-current side of a grid-controlled rectifier, the harmonics in the direct-current output voltage increase very considerably in value as the instant of arc ignition is retarded. This influence may be gauged from consideration of the analysis of the output voltage wave in the general case where the arc commutation is delayed by the angle α through the medium of grid-control. Referring to the analysis at the commencement of the present chapter, which related to the particular case where $\alpha = 0$, the rectified voltage may again be expressed by the Fourier series

$$\begin{aligned} F(\theta) = A_0 &+ A_1 \cos p\theta + A_2 \cos 2p\theta + A_3 \cos 3p\theta \\ &+ \ldots A_m \cos mp\theta + \ldots + B_1 \sin p\theta \\ &+ B_2 \sin 2p\theta + B_3 \sin 3p\theta + \ldots B_m \sin mp\theta \\ &+ \ldots \end{aligned}$$

The constant term, A_0, here represents the mean output voltage V_d given by the general equation

$$V_d = E\sqrt{2} \,.\, (p/\pi) \,.\, \sin (\pi/p) \,.\, \cos \alpha \qquad . \quad . \quad (53)$$

The limits of integration for determining the coefficients of the several sine and cosine terms are in this case, however, $(\alpha - \pi/p)$

and $(\alpha + \pi/p)$ for the voltage function $F(\theta) = E\sqrt{2} \,.\, \cos\theta$. The series is then evaluated as before by

$$A_n = \frac{p}{\pi}\int_{a-\pi/p}^{a+\pi/p} F(\theta)\cos n\theta\, d\theta$$

and $$B_n = \frac{p}{\pi}\int_{a-\pi/p}^{a+\pi/p} F(\theta)\sin n\theta\, d\theta$$

Here again $n = mp$, where m is an integer. Hence

$$\begin{aligned} A_n &= \frac{E\sqrt{2} \,.\, p}{\pi}\int_{a-\pi/p}^{a+\pi/p} \cos\theta\cos mp\theta\, d\theta \\ &= \pm E\sqrt{2} \,.\, p/\pi \,.\, \sin(\pi/p) \,.\, \left[\frac{\cos(n-1)\alpha}{n-1} - \frac{\cos(n+1)\alpha}{n+1}\right] \\ &= \pm 2V_d/(n^2-1)\,[\cos n\alpha + n\sin n\alpha\tan\alpha] \end{aligned}$$

Also $$\begin{aligned} B_n &= \frac{E\sqrt{2} \,.\, p}{\pi}\int_{a-\pi/p}^{a+\pi/p} \cos\theta\sin mp\theta\, d\theta \\ &= \pm E\sqrt{2} \,.\, p/\pi \,.\, \sin(\pi/p) \,.\, \left[\frac{\sin(n-1)\alpha}{n-1} - \frac{\sin(n+1)\alpha}{n+1}\right] \\ &= \pm 2V_d/(n^2-1) \,.\, [\sin n\alpha - n\cos n\alpha\tan\alpha] \end{aligned}$$

The amplitude of the harmonic of frequency $n = mp$ is given by $\sqrt{(A_n^2 + B_n^2)}$. The r.m.s. value of the nth harmonic is therefore

$$E_n = \frac{\sqrt{[2(1 + n^2\tan^2\alpha)]}}{n^2-1}V_d. \quad . \quad . \quad . \quad (54)$$

Remembering that the displacement factor is identical with the cosine of the ignition angle, we may write equation (54) in the form

$$E_n = \frac{V_d}{n^2-1}\sqrt{\left[2\left(1 - n^2 + \frac{n^2}{\cos^2\phi}\right)\right]} \quad . \quad . \quad (55)$$

Table V and Fig. 182 give the r.m.s. values of the several harmonics at no-load, expressed as percentages of the mean output voltage V_d, for different values of the displacement factor $\cos\phi$. It is at once seen that the values corresponding to $\cos\phi = 1$ $(\alpha = 0)$ are the same as those given in Table III, as is to be expected.

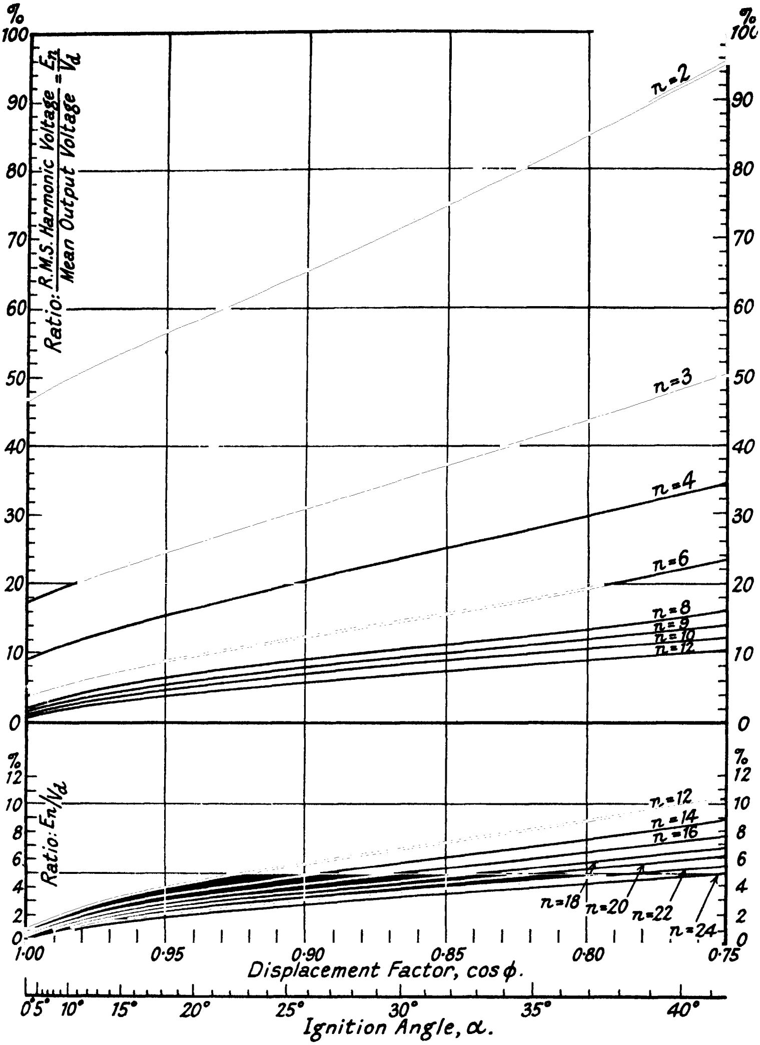

FIG. 182. RELATION BETWEEN DISPLACEMENT FACTOR AND R.M.S. VALUE OF OUTPUT-VOLTAGE HARMONICS

TABLE V

Frequency of the Harmonic	**Displacement Factor**						
	1·00	0·95	0·90	0·85	0·80	0·75	0·70
	$\alpha = 0°$	18° 12′	25° 50′	31° 48′	36° 52′	41° 24′	45° 35′
$2f$ = 100 cycles	47·13	56·55	65·65	75·00	84·90	95·50	107·00
$3f$ = 150 cycles	17·67	24·72	31·10	37·45	43·50	50·10	56·77
$4f$ = 200 cycles	9·44	15·55	20·50	25·16	29·67	34·61	39·58
$6f$ = 300 cycles	4·05	8·91	12·37	15·55	19·29	21·69	25·08
$8f$ = 400 cycles	2·25	6·29	8·98	11·37	13·54	16·11	18·45
$9f$ = 450 cycles	1·77	5·51	7·85	10·04	12·02	14·14	16·32
$10f$ = 500 cycles	1·43	4·88	7·03	8·98	10·68	12·38	14·56
$12f$ = 600 cycles	0·99	4·05	5·79	7·43	8·84	10·53	12·02
$14f$ = 700 cycles	0·73	3·32	4·95	6·22	7·55	8·90	10·32
$15f$ = 750 cycles	0·63	3·15	4·56	5·83	7·07	8·35	9·62
$16f$ = 800 cycles	0·56	2·90	4·24	5·45	6·64	7·78	8·98
$18f$ = 900 cycles	0·44	2·66	3·82	4·88	5·86	6·96	8·00
$20f$ = 1 000 cycles	0·36	2·40	3·51	4·48	5·41	6·35	7·28
$21f$ = 1 050 cycles	0·32	2·19	3·25	4·17	5·02	5·93	6·85
$22f$ = 1 100 cycles	0·29	2·12	3·10	3·96	4·79	5·62	6·45
$24f$ = 1 200 cycles	0·25	1·91	2·82	3·64	4·38	5·19	6·01

CHAPTER XV

THE CALCULATION OF RECTIFIER CIRCUIT DATA

As a general rule the starting-point in the design of any rectifier installation is the direct-current output, expressed in terms of the full-load direct voltage V_d and the full-load continuous current I_d. The calculation of the rectifier circuit data then proceeds by stages, of which the most important is the determination of the main design elements of the rectifier transformer, whereby it is assumed that the electrical constants of the alternating-current supply system are known.* The design of the rectifier itself is largely determined by the overloads it is called upon to carry, but it is also influenced by the value of the output voltage. For it must be borne in mind that the rectifier, unlike rotating converting plant, has no large masses which can store heat energy for an appreciable time; and that, like switchgear, its physical size is determined principally by current-carrying capacity, and not by power output as in the case of electrical machines.†

The design elements of the rectifier and transformer having been determined, the performance characteristics of the unit as a whole must next be obtained. In general, this determination is limited to a calculation of the mean output voltage, the efficiency, and the power factor of the unit at different loads, although in some cases a knowledge of the harmonics on the alternating-current and direct-current sides of the unit may also be required.

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* In what follows, the assumption is made that the output of the rectifier installation is negligible in comparison with the capacity of the supply system, so that the voltage of the latter remains unchanged in form and magnitude, whatever may be the nature and amount of the load on the rectifier. Such an assumption is quite reasonable except, possibly, in the comparatively rare case where a large number of traction rectifier substations, for example, constitute the base load of an isolated e.h t. network. In this case the rectifier load as a whole has a considerable effect on the circuit conditions on the alternating-current side of each rectifier substation, and any design data will have to be corrected to allow for the presence of supply reactance. The calculation of this correction in a very simple instance, that of a rectifier unit forming the sole generator load, is considered by Dallenbach and Gerecke in a paper referred to in the author's preface. Another aspect, that of rectifier power factor, has been treated somewhat more generally in a recent paper by the author published in the *Journal of the Institution of Electrical Engineers* (Vol. 72, 1933, p. 435).

† Broadly speaking, for a rectifier of given physical size, the maximum continuous rating in amperes is inversely proportional to the square root of the direct-current output voltage.

General Considerations. As with all other calculations of this kind, the required design data cannot all be obtained directly. The majority must be derived by successive approximation from certain basic assumptions regarding losses and reactive voltage drop.

As a first approximation, the effect of transformer reactance may be neglected entirely, and the main transformer data can then be obtained directly from the given full-load output current I_d and the ideal full-load voltage at the direct-current terminals as determined by

$$V_d' = V_d + e_a + e_c \quad . \quad . \quad . \quad . \quad . \quad (56)$$

where V_d is the given full-load voltage, e_a is the arc drop of the rectifier, and e_c the voltage drop due to copper losses in the transformer [*cf.* equation (10)].

The next stage in the calculations is to determine the actual drop in output voltage occasioned by reactance in the rectifier transformer. The transformer reactance is generally expressed as the reactive voltage drop in the transformer, at rated primary current, taken as a percentage of the rated no-load voltage, and is accordingly specified as x per cent, based on the primary kVA-rating of the transformer. Consequently, we have

$$x = I'X'/E' \times 100 \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

where X' is the primary reactance per phase expressed in ohms. The equivalent secondary reactance per phase X is then given by

$$X = X'/N^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

where N is the turns-ratio of the transformer. The absolute drop in direct-current volts due to this reactance is equal to

$$\begin{aligned} e_r &= V_{d_0} \,.\, \sin^2\frac{u}{2} = E\sqrt{2} \,.\, \frac{p}{\pi} \sin\frac{\pi}{p} \,.\, \left[\frac{I_d X}{(2E\sqrt{2}) \,.\, \sin(\pi/p)}\right] \\ &= (p/2\pi) \,.\, I_d X \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (59) \end{aligned}$$

From this we obtain, finally,

$$\cos^2(u/2) = V_d'/V_{d_0} = V_d'/(V_d' + e_r) \quad . \quad . \quad (60)$$

from which the angle of overlap u is determined.

It is now necessary to repeat the calculations, revising the transformer data so as to take into account the effects of overlap by means of the several current reduction factors $\sqrt{[1 - p \cdot \psi(u)]}$. In this way a new value of e_r is obtained, giving a second approximation for the angle of overlap. In most cases this latter approximation will be sufficiently accurate for all practical purposes, but a final check may be made on the resulting figures by making use of this fresh value of u in repeating the calculations once more.

Finally, it is necessary to take into account the magnetizing current of the rectifier transformer. On the assumption of certain percentage values for the transformer iron losses W_i and magnetizing current, the power component I_i and the reactive component I_m of the no-load current I_0 taken by the transformer may be determined. As explained in the preceding chapter, the components of the primary current I' of the transformer are the power component $I_P' = \lambda_0 I'$, the reactive component $I_R' = I' \cdot \mu \sin \phi = I' \cdot \lambda_0 \tan \phi$, and the harmonic component

$$I_H' = I'\sqrt{(1 - \mu^2)} = I'\sqrt{[1 - (\lambda_0^2/\cos^2 \phi)]}$$

These may be determined from the relations

$$\lambda_0 = \frac{\text{kW input to rectifier transformer}}{\text{kVA input to rectifier transformer}} = \frac{V_d' I_d}{W_1} \quad . \quad (61)$$

and $\cos \phi$

$$= \frac{\text{ideal full-load output voltage}}{\text{no-load output voltage}} = \frac{V_d'}{V_{d_i}} = \cos^2 \frac{u}{2} \quad . \quad (62)$$

The corrected primary current is then

$$I'' = \sqrt{[(I_P' + I_i)^2 + (I_R' + I_m)^2 + (I_H')^2]} \quad . \quad . \quad (63)$$

from which the figure for the primary copper loading W_1 may in turn be corrected, as may also the mean kVA rating W.

The last stage in the calculations is the determination of the operating characteristics of the rectifier unit. The efficiency is given by the ratio

$$\frac{\text{kW output of rectifier}}{\text{kW input to transformer}},$$

and its value at full load is thus given by

$$\eta = \frac{V_d I_d}{V_d' I_d + W_i} \quad . \quad . \quad . \quad . \quad . \quad . \quad (64)$$

The power factor is given by

$$\lambda = (I_P' + I_i)/I'' \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

whilst the direct-current terminal voltage may be found from

$$V_d = V_{d_0} - e_a - e_c - e_r \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

in which e_c and e_r are both directly proportional to the load current I_d, whilst e_a may be assumed constant.

The Design of a Typical Steel-tank Rectifier Unit for Traction Service. The design data are required for a six-phase steel-tank rectifier unit having a full-load direct-current output of 2 000 kW at 1 500 volts, and capable of carrying the following overloads—

$$\begin{cases} \text{25 per cent for 2 hours,} \\ \text{50 per cent for 15 minutes,} \\ \text{100 per cent for 15 seconds,} \\ \text{200 per cent momentarily.} \end{cases}$$

The three-phase alternating-current supply to the unit is at 33 000 volts and has a frequency of 50 cycles per second. The rectifier transformer is to have a reactance of 8 per cent and its magnetizing current is not to exceed 5 per cent at rated primary voltage, whilst the iron and copper losses are to be taken as ¾ per cent and 1⅛ per cent respectively. The arc drop in the rectifier is to be assumed constant at 25 volts.

(A) STEEL-TANK RECTIFIER. The full-load current output is

$$I_d = \frac{2\,000}{1\,500} \times 1\,000 = 1\,333 \text{ A.}$$

Bearing in mind the fact that for a rectifier any rating in excess of a half-hour rating must be considered as a continuous rating, then the M.C.R. of the rectifier is $1{\cdot}25 \times I_d = 1\,667$ A. Moreover, as the M.C.R. is, as a rule, based on direct-current pressures below 500 volts, the equivalent M.C.R. of the rectifier becomes $1\,667 \times \sqrt{(1\,500/500)} = 2\,890$ A. It is this 500-volt M.C.R. which determines the actual "tank size" of the rectifier, so that in this particular case the nearest standard tank is likely to be one rated at 3 000 A.

The amount of cooling water required is determined by the energy lost in the arc, which loss is manifested as heat dissipated to the circulating water, and radiated away to the surroundings of the rectifier. The heat lost to the surroundings is only a very small proportion of the total, so that one may assume the entire kW-loss in the arc to be carried away by the cooling water. The power lost in the arc at full load is

$$W_a = e_a I_d = \frac{25 \times 1\,333}{1\,000} = 33{\cdot}3\,\text{kW}.$$

Assuming an inlet water temperature of 15° C. and a maximum outlet temperature of 45° C., the amount of cooling water* required at full load will be

$$C = \frac{33{\cdot}3 \times 860}{(45 - 15) \times 1\,000} = 0{\cdot}946\,\text{cub.m. per hr.} = 208\,\text{gal. per hr.}$$

(B) RECTIFIER TRANSFORMER. For a six-anode rectifier carrying more than 1 000 A continuously, it is usual to adopt a phase-equalizing connection so as to reduce the r.m.s. anode loading. At the same time the utility factor of such a connection is higher than that of a simple six-phase connection such as the fork circuit discussed in Chapter V. In this case, therefore, the choice of transformer connection will naturally fall upon the double three-phase circuit employing a single phase-equalizing choke coil connected in the neutral point.

The ideal full-load voltage at the direct-current terminals of the rectifier unit, i.e. the full-load voltage which would be obtained if there were no losses in the unit, is found from equation (56) to be

$$V_d' = 1\,500 + 25 + \frac{1{\cdot}33 \times 2\,000 \times 1\,000}{100 \times 1\,333} = 1\,545\,\text{V}$$

(1) *First Approximation.* From Table II and Chapter V we have

$$W_1 = 1{\cdot}05 \times 1\,545 \times 1\,333 = 2\,165\,\text{kVA},$$
$$W_2 = 1{\cdot}48 \times 1\,545 \times 1\,333 = 3\,050\,\text{kVA},$$
$$W\dagger = 1{\cdot}35 \times 1\,545 \times 1\,333 = 2\,780\,\text{kVA}.$$

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* In this connection it is to be remembered that in most designs of steel-tank rectifier thermostatic control is adopted to regulate the cooling water-flow in accordance with the rectifier load. The actual cooling water consumption over a given period of time will therefore be given by the expression

$$C \times (\text{Load Factor}) \times (\text{No. of Running Hours}).$$

† Including the equivalent kVA rating of the phase equalizer.

Furthermore, we have

$$\text{R.M.S. primary phase voltage, } E' = \frac{33\,000}{\sqrt{3}} = 19\,050 \text{ volts}$$

and—

$$\text{R.M.S. secondary phase voltage, } E = 0{\cdot}855 \times 1\,545$$
$$= 1\,320 \text{ volts.}$$

Hence the turns-ratio of the transformer is

$$N = \frac{19\,050}{1\,320} = 14{\cdot}42.$$

The primary current, $I' = \frac{W_1}{3E'} = \frac{2\,165}{3 \times 19\,050} = 38$ A.

From equation (57) the primary reactance per phase is found to be

$$X' = \frac{8}{100} \times \frac{19\,050}{38} = 40{\cdot}15 \text{ ohms.}$$

so that the equivalent secondary reactance per phase, as given by equation (58), is

$$X = \frac{40{\cdot}15}{(14{\cdot}42)^2} = 0{\cdot}193 \text{ ohm.}$$

From equation (59) the drop in direct-current volts, between no-load and full-load, due to this reactance is

$$e_r = \frac{3}{2\pi} \times \frac{1\,333}{2} \times 0{\cdot}193 = 61{\cdot}4 \text{ volts.}$$

because in this particular case, with double three-phase operation of the rectifier, only *half* the load current is being commutated in each three-phase system (so that $p = 3$, and $I_d = \frac{1\,333}{2}$ in the formula for e_r).

Consequently the no-load voltage at the direct-current terminals is

$$V_{d_0} = V_d' + e_r = 1\,545 + 61{\cdot}4 = 1\,606{\cdot}4 \text{ volts.}$$

Finally, from equation (60) we obtain

$$\cos^2\frac{u}{2} = \frac{1\,545}{1\,606{\cdot}4} = 0{\cdot}9618$$

giving $u = 22^\circ\ 32'$ for the angle of overlap.

(2) *Second Approximation.* In the present case, where the rectifier operates on the double three-phase system, with $p = 3$, the *current reduction-factor* is $\sqrt{[1 - 3\,.\,\psi\,(u)]}$, which, from Fig. 14 or equation (9), has the value 0·975. All r.m.s. current values and, consequently, the several kVA ratings also, must therefore be reduced by 2·5 per cent. The corrected value for the ideal kW output of the rectifier is

$$W_d = 1\,606{\cdot}4 \times 1\,333 = 2\,120\ \text{kW},$$

so that the kVA ratings of the transformer now become

$$W_1 = 0{\cdot}975 \times 1{\cdot}05 \times 2\,120 = 2\,190\ \text{kVA},$$

$$W_2 = 0{\cdot}975 \times 1{\cdot}48 \times 2\,120 = 3\,090\ \text{kVA},$$

and $$W = 0{\cdot}975 \times 1{\cdot}35 \times 2\,120 = 2\,815\ \text{kVA}.$$

The primary current now has the value

$$I' = \frac{2\,190}{3 \times 19\,050} = 38{\cdot}37\ \text{A}.$$

The corrected secondary phase pressure is

$$E = 0{\cdot}855 \times 1\,606{\cdot}4 = 1\,373\ \text{volts},$$

so that the transformer turns-ratio becomes

$$N = \frac{19\,050}{1\,373} = 13{\cdot}87.$$

The secondary reactance per phase is accordingly

$$X = \frac{8}{100} \times \frac{19\,050}{38{\cdot}4} \times \frac{1}{(13{\cdot}87)^2} = 0{\cdot}2064\ \text{ohms}.$$

The corrected value for the direct-current voltage drop due to reactance is therefore

$$e_r = \frac{3}{2\pi} \times \frac{1\,333}{2} \times 0{\cdot}2064 = 65{\cdot}7\ \text{volts}.$$

The no-load pressure at the direct-current terminals thus becomes

$$V_{d_0} = 1\,545 + 65{\cdot}7 = 1\,610{\cdot}7 \text{ V},$$

giving

$$\cos^2 \frac{u}{2} = \frac{1\,610{\cdot}7}{1\,545} = 0{\cdot}9592.$$

From this we obtain the corrected value $u = 23^\circ\ 18'$ for the angle of overlap.

(3) *Final Check.* Making use of this new value of u we obtain 0·9745 as the final value of the current reduction-factor $\sqrt{[1 - p\,.\,\psi(u)]}$. On repeating the calculation we find: $W_d = 2\,148$ kW, $W_1 = 2\,200$ kVA, $W_2 = 3\,100$ kVA, $W = 2\,830$ kVA, $I' = 38{\cdot}5$ A, $E = 1\,377$ V, $N = 13{\cdot}83$, $X = 0{\cdot}207\ \Omega$, and $e_r = 66$ V, from which $V_{d_0} = 1\,611$ V and $\cos^2(u/2) = 0{\cdot}959$. This gives a final value $u = 23^\circ\ 20'$ for the angle of overlap, which differs only very slightly from the previous value.

Accordingly, we now obtain the following principal design elements—

Anode current,

$$I = 0{\cdot}9745 \times 0{\cdot}289 \times 1\,333 = 375 \text{ A},$$

Primary current,

$$I' = 0{\cdot}9745 \times 0{\cdot}408 \times 1\,333 \times 1/13{\cdot}83 = 38{\cdot}5 \text{ A},$$

Secondary phase voltage,

$$E = 0{\cdot}855 \times 1\,611 = 1\,377 \text{ V},$$

Primary phase voltage,

$$E' = 0{\cdot}577 \times 33\,000 = 19\,050 \text{ V},$$

Secondary copper loading,

$$W_2 = 0{\cdot}9745 \times 1{\cdot}48 \times 1\,611 \times 1\,333 = 3\,100 \text{ kVA},$$

Primary copper loading,

$$W_1 = 0{\cdot}9745 \times 1{\cdot}05 \times 1\,611 \times 1\,333 = 2\,190 \text{ kVA},$$

Mean transformer rating,

$$W = 0{\cdot}9745 \times 1{\cdot}35 \times 1\,611 \times 1\,333 = 2\,830 \text{ kVA}.$$

(4) *Correction for Magnetizing Current.* The magnetizing current proper is $I_m = 0{\cdot}05 \times 38{\cdot}5 = 1{\cdot}92$ A, whilst the in-phase component due to iron loss is $I_i = 0{\cdot}0075 \times 38{\cdot}5 = 0{\cdot}29$ A.

To determine the several components of the primary current, we have, firstly, from equation (61)

$$\lambda_0 = \frac{1\,545 \times 1\,333}{2\,190 \times 1\,000} = 0{\cdot}943$$

and, secondly, from equation (62)

$$\cos\phi = \frac{1\,545}{1\,611} = 0{\cdot}959 \text{ (with } \tan\phi = 0{\cdot}296)$$

Hence the power component is

$$I_P' = 0{\cdot}943 \times 38{\cdot}5 = 36{\cdot}3 \text{ A},$$

whilst the reactive component is

$$I_R' = 0{\cdot}943 \times 0{\cdot}296 \times 38{\cdot}5 = 10{\cdot}7 \text{ A}.$$

Similarly, the harmonic component is

$$I_H' = 38{\cdot}5 \times \sqrt{\left[1 - \left(\frac{0{\cdot}943}{0{\cdot}959}\right)^2\right]} = 7{\cdot}0 \text{ A}.$$

From equation (63) the corrected value of the primary current is then

$$\begin{aligned} I'' &= \sqrt{[(36{\cdot}3 + 0{\cdot}29)^2 + (10{\cdot}7 + 1{\cdot}92)^2 + (7{\cdot}0)^2]} \\ &= \sqrt{(1\,337 + 160 + 49)} = 39{\cdot}2 \text{ A}, \end{aligned}$$

which is some 2·4 per cent greater than the figure previously obtained. Consequently the primary copper loading finally becomes

$$W_1 = 1{\cdot}024 \times 2\,190 = 2\,240 \text{ kVA},$$

so that the final value of the mean transformer rating is $W = 2\,855$ kVA.

(5) *Phase Equalizer.* The phase-equalizing choke coil, considered as a 50-cycle single-phase transformer, has an equivalent rating of approximately

$$0{\cdot}083 \times 1\,611 \times 1\,333 = 180 \text{ kVA}.$$

Each of its two windings must be capable of continuously carrying half the full-load output current of the rectifier, or 667 A. As explained in Chapter V, the voltage across the phase equalizer may be taken as half the secondary phase voltage of the rectifier transformer, or approximately 690 volts.

The voltage per winding is therefore 345 volts, and has a frequency of 150 cycles per second.

The triple-harmonic magnetizing current in each winding is carried by half the load current I_d, so that the critical load current must be equal to twice the amplitude of the magnetizing current. Assuming a critical load of 0·5 per cent of full load, then the magnetizing current of the phase equalizer must have an r.m.s. value

$$I_{m_3} = 0{\cdot}707 \times \frac{0{\cdot}005 \times 1\,333}{2} = 2{\cdot}4 \text{ A.}$$

The reactance per winding at third-harmonic frequency is therefore

$$X_3 = \frac{690}{2{\cdot}4} = 290 \text{ ohms,}$$

so that the inductance per winding must be

$$L = \frac{X_3}{3\omega} = \frac{290}{3 \times 2\pi \times 50} = 0{\cdot}154 \text{ henries.}$$

(C) Performance Characteristics. The full-load efficiency of the rectifier unit is found from equation (64) to be

$$\eta = \frac{2\,000}{(1\,545 \times 1\,333) + (0{\cdot}0075 \times 2\,000)} = \frac{2\,000}{2\,060 + 15} = 0{\cdot}965$$

whilst from equation (65) the power factor at full load is, similarly,

$$\lambda = \frac{36{\cdot}28 + 0{\cdot}29}{39{\cdot}21} = 0{\cdot}932.$$

Finally, from equation (11) the drop in output voltage* from the critical load to full load is found to be

$$r = 100 \times \left(\frac{66 + 20}{1\,611 - 25}\right) = \frac{86}{1\,586} = 5{\cdot}42 \text{ per cent.}$$

The direct-current terminal pressure at no-load is, of course, given by

$$\left(\frac{1\,377}{0{\cdot}74}\right) - 25 = 1\,836 \text{ volts,}$$

which is 16 per cent higher than at the critical load of 7 A.

---

* Generally referred to as the *regulation* of the unit.

TABLE VI

Symbol	Unit	$\frac{1}{4}$ Load	$\frac{1}{4}$ Load	$\frac{3}{4}$ Load	$\frac{4}{4}$ Load	$\frac{5}{4}$ Load	$\frac{6}{4}$ Load
I_d	A	333	667	1 000	1 333	1 667	2 000
V_{do}	V	1 611	1 611	1 611	1 611	1 611	1 611
e_r	V	16·5	33	49·5	66	82·5	99
V_d'	V	1 594·5	1 578	1 561·5	1 545	1 528·5	1 512
e_a	V	25	25	25	25	25	25
e_c	V	5	10	15	20	25	30
V_d	V	1 564·5	1 543	1 521·5	1 500	1 478·5	1 457
r	%	1·4	2·7	4·1	5·4	6·8	8·1
V_dI_d	kW	521·5	1 029	1 521·5	2 000	2 465	2 914
$(V_d'I_d + W_i)$	kW	546·5	1 065	1 576·5	2 075	2 562·5	3 039
η	%	95·4	96·6	96·7	96·5	96·2	95·9
$\cos^2(u/2)$	—	0·9897	0·9795	0·9694	0·9490	0·9485	0·9387
u	—	11° 39′	16° 27′	20° 9′	23° 20′	26° 14′	28° 40′
$\sqrt{[1 - p \cdot \psi(u)]}$	—	0·9875	0·9815	0·9782	0·9745	0·9715	0·9685
I	A	95	189	273	375	468	560
I'	A	9·7	19·4	28·9	38·5	47·8	57·3
λ_o	%	95·5	95·2	94·6	94·3	93·5	92·7
$\cos\phi$	—	0·990	0·980	0·969	0·959	0·949	0·939
μ	—	0·966	0·972	0·976	0·983	0·986	0·989
$\lambda_o \tan\phi$	%	13·8	19·5	23·9	27·8	31·2	37·8
$\sqrt{(1-\mu^2)}$	%	26·3	24·5	20·6	18·2	16·8	15·7
I_P'	A	9·3	18·5	27·3	36·3	45·0	53·2
I_R'	A	1·3	3·8	6·9	10·7	14·9	21·7
I_H'	A	2·5	4·7	5·9	7·0	8·1	9·0
I_i	A	0·3	0·3	0·3	0·3	0·3	0·3
I_m	A	1·9	1·9	1·9	1·9	1·9	1·9
I''	A	10·4	20·2	29·6	39·2	49·1	59·2
λ	%	91·8	93·1	93·3	93·2	92·3	90·8

The main design data appropriate to different loads are collected in Table VI from which the performance characteristics of Fig. 183 are derived.

The Design of a Multiple-unit Glass-bulb Rectifier Installation for Lighting and Power Supply. The design data are required for a twelve-phase glass-bulb rectifier equipment to supply 600 kW across the outers of a 250/500 volt three-wire direct-current system and to withstand overloads of

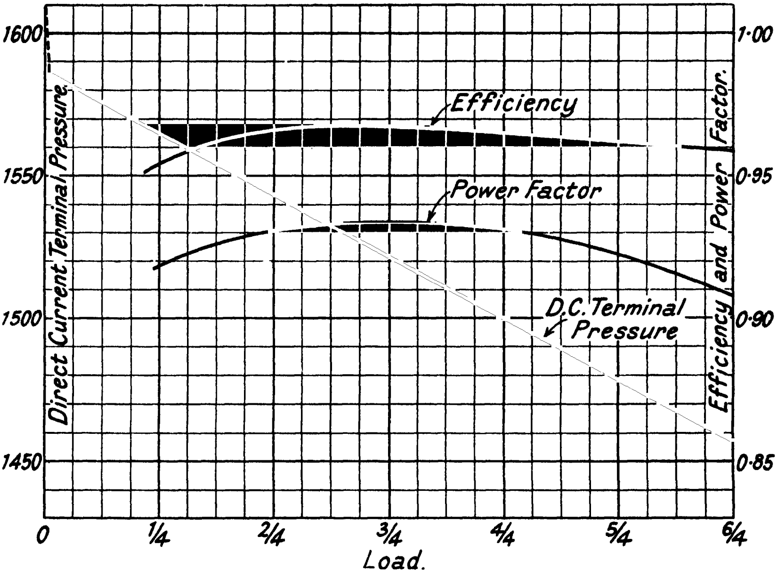

FIG. 183. PERFORMANCE CHARACTERISTICS OF A 2 000-KW, 1 500-VOLT STEEL-TANK RECTIFIER UNIT

$$\begin{cases} 25 \text{ per cent for } 2 \text{ hours,} \\ 50 \text{ per cent for } 15 \text{ minutes,} \\ 100 \text{ per cent for } 15 \text{ seconds.} \end{cases}$$

The equipment is to run in parallel with rotary converting plant having a level-compound voltage characteristic. The alternating-current supply is three-phase at 6 600 volts and 50 cycles per second. The rectifier transformer may be assumed to take a 6 per cent magnetizing current, whilst the iron and copper losses are to be taken as 1 per cent and 2 per cent respectively. The arc drop in the glass-bulb rectifiers is to be assumed constant at 21 volts.

(A) GLASS-BULB RECTIFIERS. The full-load output current is

$$I_a = \frac{600 \times 1\,000}{500} = 1\,200 \text{ A}$$

so that the M.C.R. of the equipment will be 1·25 × 1 200 = 1 500 A. For this output four bulbs are necessary, each being rated at 375 A. The nearest standard rectifier bulb rating is likely to be 400 A. The 50 per cent overload rating corresponds to 1 800 A for 15 min., or 450 A per bulb for that period. This represents only slightly over a 10 per cent overload based on the standard rating, which is well within the capacity of a modern glass-bulb rectifier.

The heat energy liberated in each bulb at full load has to be dissipated at the rate of 21 × 300 = 6·3 kW, or 21 500 B.Th.U. per hour. For this purpose some 6 500 cub. ft. of cooling air per minute will be necessary.*

(B) RECTIFIER TRANSFORMER. Of the several twelve-phase circuits discussed in Chapter VI, the "series" circuit has the advantage of embodying the principle of phase equalizing without producing a sudden and sharp rise in output voltage in the no-load region. In this respect it is somewhat superior to the quadruple three-phase circuit, whilst the mean kVA-rating of the transformer unit is the same in both cases. Preference will in this case, therefore, be given to the twelve-phase series connection. Two rectifier bulbs will be supplied from each fork-connected secondary winding, so that the outer stretches must be split, providing two parallel paths of appreciable impedance for the currents taken by pairs of anodes operating in parallel.† The r.m.s. anode current at full load is then found, from equation (24*b*), to be

$$I_1 = \tfrac{1}{2} \times 0{\cdot}173 \times 1\,200 = 104 \text{ A},$$

---

* The author has found from experience that a useful empirical rule for determining the quantity of cooling air required is to allow 3 cub. ft. per min. for every 10 B.Th.U. to be dissipated per hour; or approximately 1 cub. ft. per min. for every watt lost in the arc. This rule, of course, only applies in the case of normal room temperatures and where a properly designed air-flow around the bulb has been obtained.

† Alternatively, special centre-tapped anode choke coils must be provided, designed to give an impedance drop in each half-winding of about 15–20 volts at full load.

a figure which is within the limits of a 400-A rectifier bulb,[*] even when taking into account the specified overload of 25 per cent for 2 hours.

The ideal full-load voltage at the direct-current terminals of the rectifier equipment is

$$V_d' = 500 + 21 + \frac{2 \times 600 \times 1\,000}{100 \times 1\,200} = 531 \text{ V}.$$

As grid-control will be employed to maintain the voltage constant at all loads, one may allow a fairly large reactance drop in the transformer. If a 7 per cent drop in output voltage between no-load and full-load is assumed, then the ideal no-load terminal pressure becomes

$$V_{d_0} = \frac{531}{0{\cdot}93} = 571 \text{ V},$$

so that the actual no-load direct voltage is $(571 - 21) = 550$ volts. The drop due to transformer reactance is $e_r = 40$ volts. As the rectifier circuit operates on the four-phase system (*cf.* Chapter VI) and only half the load current is commutated in each of the two secondary windings,[†] equation (59) gives

$$40 = \frac{4}{2\pi} \times \frac{1\,200}{2} \times X,$$

from which the equivalent secondary reactance per phase $X = 0{\cdot}1047$ ohm.

The angle of overlap at full load is found from

$$\cos^2 \frac{u}{2} = \frac{V_d'}{V_{d_0}} = \frac{531}{571} = 0{\cdot}93$$

to be $u = 30^\circ\ 41'$. The reduction factor for the anode currents is, therefore, $\sqrt{[1 - 4\psi(u)]} = 0{\cdot}955$. As the inner stretches of the secondary winding are utilized twice as often as the outer stretches, the reduction factor for the secondary currents is $\sqrt{[1 - 2\psi(u)]} = 0{\cdot}978$. The primary currents have a reduction factor[‡] $\sqrt{[1 - \kappa.\ \psi(u)]}$, where $\kappa = p(1 - \cos 2\pi/p)$, which in this case becomes $\sqrt{[1 - 1{\cdot}61\psi(u)]} = 0{\cdot}982$. The total primary copper loading is consequently

---

[*] The limiting r.m.s. anode current in modern bulbs of this size varies from about 120 to 150 A.

[†] Strictly speaking, the load current divides between the two transformers in the ratios $2 : \sqrt{3}$, and $\sqrt{3} : 2$ during alternate twelfths of the anode voltage cycle. For all practical calculations the effect produced is the same as if the division were symmetrical and in the ratio 1 : 1.

[‡] *Cf.* the author's *Fundamental Theory of Arc Convertors*, pp. 93 and 94, equations (84) and (85).

$$W_1 = 0{\cdot}982 \times 1{\cdot}03 \times 571 \times 1\,200 = 695 \text{ kVA},$$

so that the input current to the transformer bank is

$$I' = \frac{695 \times 1\,000}{\sqrt{3} \times 6\,600} = 61 \text{ A}.$$

The secondary phase voltage is, from equation (24*a*),

$$E = 0{\cdot}785 \times 571 = 448{\cdot}5 \text{ volts},$$

and the corresponding voltages across the inner and outer stretches of the windings are thus $E_1 = E_2 = 259$ volts.

Equations (57) and (58) combine to give the following simple expression for the percentage transformer reactance

$$x = \frac{100}{3} \times \frac{W_1X}{(E)^2} = \frac{100 \times 695 \times 0{\cdot}1047}{3 \times (448{\cdot}5)^2} = 12{\cdot}6 \text{ per cent.}$$

This comparatively high reactance value allows of a concentric type of winding being used without sacrifice of mechanical strength as regards withstanding the heavy short-circuit stresses set up during a possible back-fire—although in the case of a glass-bulb rectifier equipment this factor is really of little consequence, as suitable protection is afforded by anode fuses.

It is now possible to deduce the main elements of the transformer design, as follows—

Anode current,

$$I_1 = \tfrac{1}{2} \times 0{\cdot}955 \times 0{\cdot}173 \times 1\,200 = 100 \text{ A},$$

Secondary current,

$$I_2 = 0{\cdot}978 \times 0{\cdot}268 \times 1\,200 = 315 \text{ A},$$

Secondary phase voltage,

$$E = 0{\cdot}785 \times 571 = 448{\cdot}5 \text{ V},$$

Voltage per secondary stretch,

$$E_1 = E_2 = \frac{E}{\sqrt{3}} = 259 \text{ V},$$

Star-primary phase voltage,

$$E_Y' = \tfrac{1}{2} \times \frac{6\,600}{\sqrt{3}} = 1\,905 \text{ V},$$

Delta-primary phase voltage,

$$E_\Delta' = \frac{\sqrt{3}}{2} \times \frac{6\,600}{\sqrt{3}} = 3\,300 \text{ V},$$

Star-primary phase current,

$$I_Y' = 0{\cdot}983 \times 0{\cdot}438 \times 1\,200 \times \frac{448{\cdot}5}{3\,810} = 61 \text{ A},$$

Delta-primary phase current,

$$I_\Delta' = 0{\cdot}983 \times 0{\cdot}253 \times 1\,200 \times \frac{448{\cdot}5}{3\,810} = 35 \text{ A},$$

Total secondary copper loading,

$$W_2 = 0{\cdot}983 \times 1{\cdot}67 \times 571 \times 1\,200 = 1\,125 \text{ kVA},$$

Total primary copper loading,

$$W_1 = 0{\cdot}983 \times 1{\cdot}03 \times 571 \times 1\,200 = 695 \text{ kVA},$$

Mean transformer rating,

$$W = \tfrac{1}{2}(695 + 1\,125) = 910 \text{ kVA}.$$

The magnetizing current is $I_m = 0{\cdot}06 \times 61 = 3{\cdot}6$ A, whilst the in-phase component of the no-load current is $I_i = 0{\cdot}01 \times 61 = 0{\cdot}6$ A. To determine the components of the primary current, we have

$$\lambda_0 = \frac{531 \times 1\,200}{695 \times 1\,000} = 0{\cdot}916,$$

and $\cos\phi = \dfrac{531}{571} = 0{\cdot}930$ (with $\tan\phi = 0{\cdot}3952$),

so that $\mu = \dfrac{0{\cdot}916}{0{\cdot}930} = 0{\cdot}985.$

Hence the power component is

$$I_P' = 0{\cdot}916 \times 61 = 56 \text{ A},$$

the reactive component is

$$I_R' = 0{\cdot}916 \times 0{\cdot}3952 \times 61 = 22 \text{ A},$$

and the harmonic component is

$$I_H' = 61 \times \sqrt{[1 - (0{\cdot}985)^2]} = 10{\cdot}5 \text{ A}.$$

Consequently the corrected value of the primary current is

$$I'' = \sqrt{[(56 + 0{\cdot}6)^2 + (22 + 3{\cdot}6)^2 + (10{\cdot}5)^2]}$$
$$= \sqrt{(3\,193 + 655 + 110)} = 63 \text{ A}.$$

This is 3½ per cent greater than the figure previously obtained. The final value for the primary copper loading is therefore

$$W_1 = 1{\cdot}035 \times 695 = 725 \text{ kVA},$$

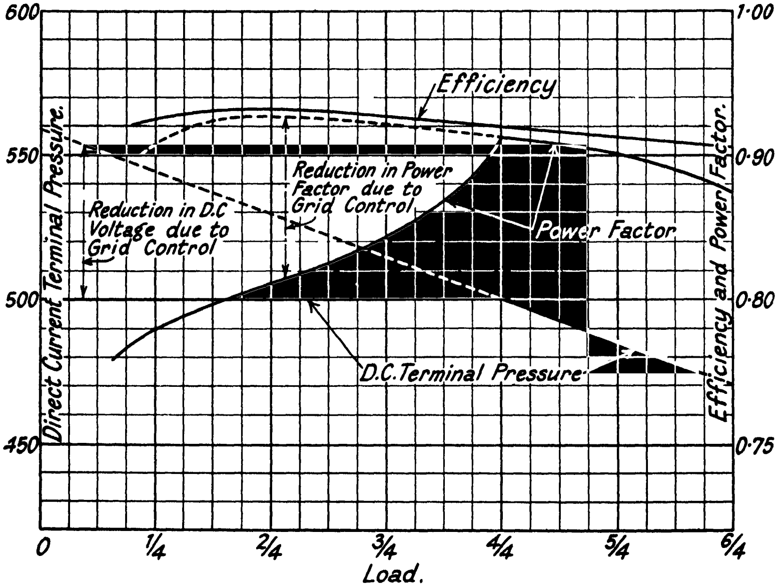

FIG. 184. PERFORMANCE CHARACTERISTICS OF 600-KW, 500-V GLASS-BULB RECTIFIER EQUIPMENT

so that the mean transformer rating finally becomes

$$W = 925 \text{ kVA}.$$

(C) PERFORMANCE CHARACTERISTICS. The full-load efficiency of the equipment is

$$\eta = \frac{600}{(531 \times 1{\cdot}2) + (0{\cdot}01 \times 600)} = \frac{600}{637 + 6}$$
$$= 0{\cdot}934,$$

TABLE VII

Symbol	Unit	$\frac{1}{4}$ Load	$\frac{2}{4}$ Load	$\frac{3}{4}$ Load	$\frac{4}{4}$ Load	$\frac{5}{4}$ Load	$\frac{6}{4}$ Load
I_d	A	300	600	900	1 200	1 500	1 800
V_{d_0}	V	580	580	580	571	580	580
e_r	V	10	20·5	31	41	51	61·5
V_d'	V	570	559·5	549	531	529	518·5
e_a	V	21	21	21	21	21	21
e_c	V	4·5	9	13·5	18	22·5	27
V_d	V	544·5	529·5	514·5	500	485·5	470·5
$V_d I_d$	kW	164	318	463	600	728	847
$(V_d' I_d + W_i)$	kW	177	342	500	653	800	932
η	%	92·4	93·2	92·6	91·9	91·2	90·8
$\cos^2 (u/2)$	—	0·9828	0·9647	0·9466	0·9299	0·9122	0·8940
u	—	15° 3′	21° 40′	26° 43′	30° 41′	34° 28′	38° 0′
$\sqrt{[1 - 1{\cdot}61\psi(u)]}$	—	0·9918	0·9880	0·9852	0·9830	0·9808	0·9788
I'	A	15·5	30·9	46·3	61	76·7	92·0
λ_0	%	96·5	95·2	93·4	91·6	90·3	88·2
$\cos \phi$	—	0·982	0·965	0·947	0·930	0·902	0·894
μ	—	0·982	0·984	0·986	0·988	0·990	0·992
$\cos \alpha$	—	0·919	0·944	0·972	1·000	1·000	1·000
α	—	23° 17′	19° 14′	13° 42′	0	0	0
$\mu \sin (\phi + \alpha)$	%	54·8	55·8	52·2	36·4	40·6	44·4
$\sqrt{(1 - \mu^2)}$	%	19·0	17·9	16·8	15·4	14·2	12·6
I_P'	A	15·0	29·4	43·2	56	69·1	80·2
I_E'	A	8·5	17·3	23·1	22	31·1	40·8
I_H'	A	3·0	5·5	7·8	10·5	10·9	11·6
I_i	A	0·6	0·6	0·6	0·6	0·6	0·6
I_m	A	3·6	3·6	3·6	3·6	3·6	3·6
I''	A	20·0	37·1	52·1	63·5	77·3	92·4
λ	%	78·0	81·1	84·2	91·2	90·2	87·5

whilst the full-load power factor is

$$\lambda = \frac{56 + 0{\cdot}6}{63} = 0{\cdot}9.$$

The inherent regulation of the equipment—to be nullified by grid-control—is

$$r = \frac{550 - 500}{550} = \frac{50}{550} = 9 \text{ per cent.}$$

The ignition angle α at no-load, i.e. the angle by which the arc commutation must be retarded in order to bring the no-load terminal voltage down from 559 to 500 volts, is thus given by

$$\cos \alpha = \frac{V_d}{V_{do} - e_a} = \frac{500}{550} = 0{\cdot}909$$

from which $\alpha = 24^\circ\ 38'$. The inherent power factor at other loads is approximately given by

$$\lambda_0 = \mu \,.\, \cos (\alpha + \phi)$$

since the effect of retarding the instant of arc commutation is to reduce the power factor. At no-load, therefore, and neglecting the effect of magnetizing current, the power factor would be $\mu \cos \alpha$ instead of μ.

Table VII gives the principal design data from which the performance characteristics of Fig. 184 have been plotted.

CHAPTER XVI

SOME TYPICAL BRITISH RECTIFIER INSTALLATIONS

In concluding a work dealing very largely with the theoretical aspects of current conversion by means of mercury-arc rectifiers, it is only correct that some account should be given of how the leading principles of arc rectification are applied, not merely in the laboratories and research departments of rectifier manufacturers, not even in the course of "field" tests carried out under rather special conditions perhaps, but in normal circumstances such as make a ready appeal to those who, in the end, have to attend and maintain the actual equipments in which these principles are embodied. This chapter is accordingly devoted to a description of British practice in power rectification as typified by some examples of mercury-arc rectifier plant installed in this country during the last five years*—

(1) Steel-tank rectifier equipments for electric railway service.

(2) Glass-bulb rectifier equipments for electric railway service.

(3) Steel-bulb rectifier equipment for trolley-bus service.

(4) A fully-automatic grid-controlled steel-tank rectifier substation for municipal lighting and power supply.

(5) Grid-controlled glass-bulb rectifier equipments with a variable voltage-characteristic.

(6) A steel-tank rectifier substation for municipal lighting and power supply, and arranged for either fully-automatic or remote supervisory control.

(7) A glass-bulb rectifier unit for municipal traction service and arranged to deal with regenerated power.

(8) A remote-controlled steel-tank rectifier substation installed in a residential area.

(1) STEEL-TANK RECTIFIER EQUIPMENTS FOR ELECTRIC RAILWAY SERVICE

It is by now well established that among converting plant capable of meeting the onerous demands of electric traction service, with its rapidly varying duty-cycle involving frequent and sudden load peaks, the mercury-arc rectifier stands pre-eminent. The author had occasion to draw public attention to its marked superiority over rotating converting plant for this duty at a time when interest in the steel-tank rectifier—dormant in this country since the failure of such plant to establish itself as a commercial success in the early 'twenties—was being stimulated afresh by the decision of the London Electric Railway authorities to supply their extending underground traction system from mercury-arc rectifier substations.

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* The author is indebted to the following publications for the description and illustration of these rectifier installations—

B.T.H. Descriptive List No. 121–13. Bruce-Peebles Leaflet No. 183.

G.E.C. Installation Leaflets Nos. 27, 28, and 31. *The Engineer* (28th July, 1933). *The English Electric Journal*, Vol. VII, Nos. 1 and 2.

The factors influencing the decision to equip the substations for the Piccadilly Line extensions wholly with mercury-arc rectifiers were (1) quietness of operation, (2) parallel operation of adjacent substations fed from different power systems, (3) high efficiency at low loads, and (4) high momentary overload capacity.*

The extension from Finsbury Park to Cockfosters amounts to 7½ miles, and is designed for an ultimate service of forty-two seven-coach trains per hour in each direction. The line is served by substations at Manor House, Wood Green, Arnos Grove, Southgate, and Cockfosters. Manor House and Wood Green substations each contain three 1 500 kW rectifiers. The remaining substations will each contain two similar equipments.

The rectifier equipments are all constructed for 630 volts direct current, and have the following ratings—

1 500 kW, 2 400 A continuously,
2 250 kW, 3 600 A for one hour,
4 500 kW, 7 200 A for short periods.

In addition to the substations supplying this extension, the contract awarded to the British Thomson-Houston Co., Ltd., included two other substations, between Finsbury Park and King's Cross. One of these (at Holloway Road) contains rectifiers of 1 500 kW rating, which replaces existing equipment; the other (at York Road) contains units of 2 000 kW capacity.

All the above substations are unattended and are remotely controlled from a control room located above the Wood Green rectifier substation, from which also the 11 000-volt, 50-cycle, three-phase supply received from the North Metropolitan Electric Supply Co. is distributed to the seven substations.

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* The more general arguments in favour of steel-tank rectifiers for traction service are given in the paper read jointly by Mr. J. W. Rissik and the author before the Institution of Electrical Engineers and referred to above. (*Journal I.E.E.*, 1931, Vol. 69, pp. 933 *et seq.*)

Rectifiers. Fig. 185 illustrates one of the 1 500 kW rectifiers nstalled. They are constructed with twelve main anodes, and the following features are incorporated in their design and construction—

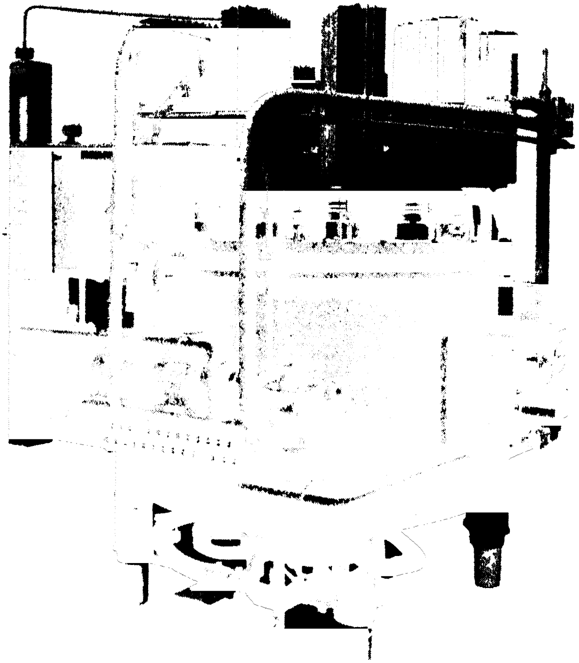

FIG. 185. 1 500-KW 630-VOLT STEEL-TANK RECTIFIER
British Thomson-Houston Co., Ltd.

The main vacuum tanks are welded by the atomic hydrogen process, giving a dense, ductile weld. The main anodes, excitation anodes, and ignition anode are mounted on a top plate, which is easily removable from the main vacuum tank by breaking one seal.

All demountable joints on the rectifier are sealed with mercury and fitted with leakage indicators, giving a flexible low-stressed seal.

All water-cooled surfaces are available for inspection without breaking the vacuum.

FIG. 186. MERCURY-VAPOUR VACUUM PUMP WITH INDUCTION HEATING
British Thomson-Houston Co., Ltd.

The mercury pump, rotary vacuum pump, pump motor, Pirani gauge generator, and water circulating pump are all mounted on the main tank, so that all this equipment can be fixed to the rectifier in the factory, thus ensuring good alignment and freedom from faulty joints.

Six-phase excitation is used, which ensures complete stability of the main arc even at the smallest possible loads. This construction also enables the rectifier to be designed with the greatest factor of safety with regard to backfire.

The mercury pump (Fig. 186) is of exceedingly high speed, and the boiler of the pump is heated by induction, so that the maximum temperature at any point on the mercury pump does not exceed approximately 200° C.—an important point where continuity of service is essential.

The anodes and anode screens are constructed of graphite, which ensures freedom from deterioration during bake-out, short-circuit, or backfire.

These rectifiers are fitted with special and exact thermal control, rendering them remarkably free from backfire.

Each rectifier is fitted with two vacuum gauges. One is manually controlled (McLeod gauge) and gives absolute readings, but is not suited for continuous readings or for automatic control. The other vacuum gauge (Pirani gauge) is an electrical device which can be calibrated from the manually-operated gauge, and is suitable for giving a continuous indication of the vacuum, and also for operating a relay in case the vacuum should fall below a predetermined figure. The Pirani gauge (Fig. 187) is of unusually robust construction, and is suitable for operating the indicating instrument and relay direct without the use of any delicate intermediate mechanism.

The cooling water for each rectifier is circulated by the water-pump on the rectifier through a closed-circuit cooling system.

FIG 187. ELECTRICAL VACUUM GAUGE AND RELAY PANEL
British Thomson-Houston Co., Ltd

A motor-operated fan forces air through the cooler (Fig. 188), and is controlled by a thermostat on the rectifier so as to run intermittently, starting up when the temperature has risen to a predetermined value and stopping again as soon as the rectifier has been cooled to a temperature a few degrees lower. The cooler is at the potential of the rectifier tank; the complete fan equipment, however, is at earth potential. The mercury pumps are cooled by water from a storage tank fitted with a ball valve and capable of maintaining the supply during any reasonable suspension of the water service.

A smoothing equipment is connected to each rectifier to ensure freedom from disturbance to telephones arising from the undulations normally associated with the output voltage. With

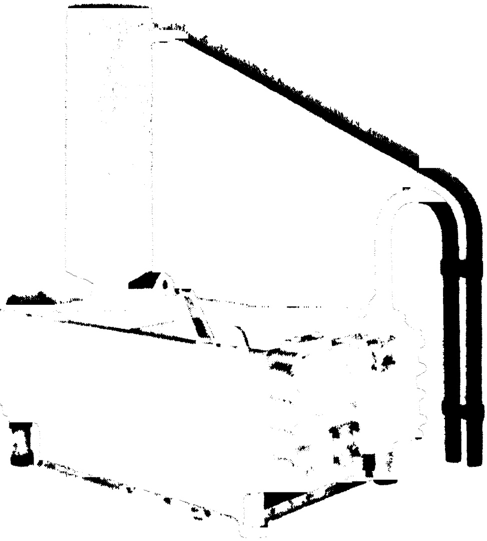

FIG. 188. AIR-BLAST RE-COOLER FOR STEEL-TANK RECTIFIER

British Thomson-Houston Co., Ltd.

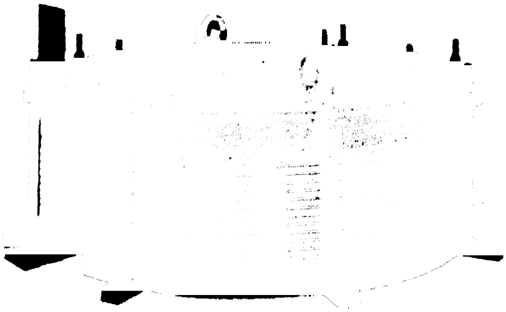

FIG. 189. AIR-CORED SMOOTHING REACTOR

British Thomson-Houston Co., Ltd.

this apparatus the undulations are reduced to approximately one-tenth of their normal value. The equipment consists of a reactor (Fig. 189) placed in series with the load, together with four resonant shunt circuits connected between the positive and negative bars, each shunt circuit containing a reactance coil and condenser and being tuned to a particular frequency. The four circuits fitted are tuned to 6, 12, 18, and 24 times the supply periodicity. If such equipments are fitted to rectifiers, the output voltage wave-shape is as satisfactory as that obtained from well designed rotating converting plant.

The rectifiers were specially designed with a view to giving excellent starting characteristics. It has long been appreciated that one of the limitations of the early rectifiers was the fact that reduced loads only could be placed on them when cold, i.e. it was necessary for the rectifier to warm up somewhat before it was safe to apply heavy overloads. This condition was avoided in the experimental equipment put into the Hendon substation by fitting the tank with a high-power heater which was used prior to connecting the rectifier to the bus-bars. In these later equipments, by special design it is now possible to connect the rectifier to the bus-bars without pre-heating and with a certainty that it will carry large overloads.

The guaranteed efficiencies, which were readily met on these equipments, including all losses in the rectifier, transformers, transformer blower, auxiliaries, smoothing circuit, and all stray losses, were as follows—

Full Load	Half Load
93·37%	93·34%

Transformers. The main transformers required for converting the 11 000-volt, three-phase supply to the voltage and number of phases required by the rectifiers, consist of three single-phase air-blast units. The primary side is connected in delta, and the secondary windings are connected parallel double three-phase, the neutral points of the stars being connected together through an interphase transformer.

The transformer cores are of cruciform type, a form which enables efficient use of the iron to be made as well as affording the excellent ventilation required in the air-blast design. Circular coils, the advantages of which are well known, are employed. Special attention has been given to the mechanical design and to the insulation of the secondary windings to render them free from damage due to voltage surges or short-circuits.

Each bank of transformers is provided with a low-voltage six-phase winding, so that by changing links on the transformer terminals, the rectifier can be supplied at a low voltage suitable for baking-out after it has been opened to atmosphere. With this arrangement, disconnection or removal of the main leads is avoided should it be necessary at any time to open one of the tanks.

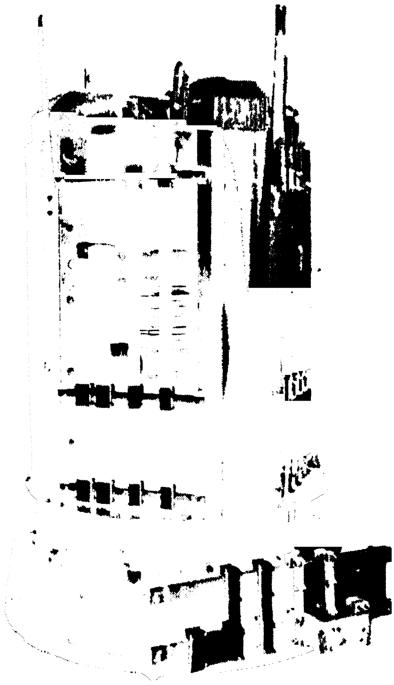

FIG. 190. MAIN TRANSFORMER WITHOUT CASING, SHOWING CORE AND COILS—AND LINKS FOR BAKING-OUT
British Thomson-Houston Co., Ltd.

Fig. 190 illustrates one of the main transformers, whilst Fig. 191 shows the interphase transformer, the air casings being removed in both cases.

The auxiliary supplies to the rectifiers, control gear, and oil switches are provided by two step-down transformers in each substation, the high-tension side of each transformer being connected to an incoming alternating-current feeder through current-limiting resistances and high-tension fuses. These transformers are self air-cooled, and step down from 11 000 volts to 220 volts, three-phase, each transformer being large enough to supply the whole of the auxiliary load in the substation.

Bake-out Equipment. A bake-out equipment is supplied in each substation, consisting of the six-phase low voltage windings fitted to each bank of main transformers, and a loading resistance. The function of this apparatus is to enable the rectifier to be operated at low voltage with gradually increasing current after the tank has been opened to atmosphere, so as to drive off occluded gas from the tank and anodes and thus make sure that when the rectifier is put in commercial service it is in a fit condition to carry its heaviest loads. The inclusion of this apparatus is desirable, since it ensures that after overhaul the plant can be put back into service in the minimum time without risk of backfire or other disturbance.

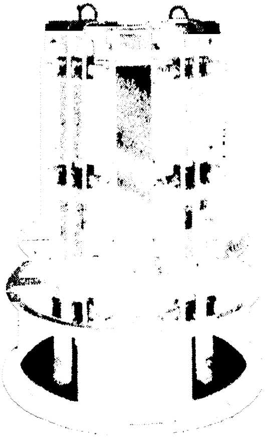

FIG. 191. INTERPHASE TRANSFORMER WITHOUT CASING
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Rectifier Control Gear. A complete control panel for a rectifier equipment is shown in Fig. 192. These panels perform all the operations necessary for starting-up, controlling, and shutting-down the rectifier when the appropriate impulses are received from Wood Green control room. As soon as the starting impulse from Wood Green, or from the local control switch, is received, the rotary pump motor starts up (the mercury pump is already operating, as it works continuously) and, providing that the various protective devices indicate that everything is correct, the excitation arc is struck, and the main oil switch closed, energizing the main transformers and starting the transformer blower motor. The voltage which immediately appears at the direct-current terminals of the rectifier then

FIG. 192 AUTOMATIC CONTROL PANEL FOR RECTIFIER UNIT
British Thomson-Houston Co, Ltd

causes the positive and negative circuit-breakers to close, whereupon the fact that the rectifier is on load is indicated at Wood Green. The total time required to put a rectifier on load, at any temperature, is about one minute. When shutting down, the stopping impulse simply trips the various circuit-breakers, and the opening of these similarly operates an indicating lamp in the control room.

The rectifier control panel also includes the apparatus for starting and stopping the recooler blower under thermostatic control.

Protection. Each rectifier is connected to the direct-current bus-bars through a reverse-current high-speed circuit-breaker on the positive side and a contactor on the negative side. The negative contactor is necessary, as the traction system operates with both positive and negative conductor rails insulated from earth.

In the event of a backfire, the reverse-current high-speed breaker would immediately open, due to current fed back into the rectifier from the bus-bars, and this is interlocked so that its opening instantly trips the main oil switch. Overload relays and an earth leakage relay are also provided on the alternating-current side, operating direct on the oil switch.

The rectifier control gear also provides protection against the following occurrences—

(*a*) Alternating-current supply voltage too low for correct operation of auxiliaries.

(*b*) Failure of vacuum.

(*c*) Excess temperature of the rectifier.

(*d*) Excess temperature of the mercury pump.

(*e*) Excess temperature of the transformers.

(*f*) Failure or stalling of the rotary pump motor.

(*g*) Failure to complete the starting operation within a definite time.

(*h*) Excessive voltage rise on the direct-current system, or breakdown of rectifier auxiliaries to earth.

In the case of (*f*), (*g*), and (*h*), the rectifier is locked out of service; but in case of the operation of any of the other protective devices, the rectifier can be started again from Wood Green as soon as the faulty condition has corrected itself.

It is a characteristic of the double three-phase transformer connection that there is a steep rise of the output voltage, amounting to 15 per cent, from about 0·4 per cent load to no-load. Although conditions will rarely arise where a load as small as this can exist, provision is made in each substation to take care of the voltage rise. The apparatus for this purpose consists of a small loading resistance which is automatically connected across the bus-bars as soon as any rise of voltage takes place, and is disconnected after a time-delay. The power consumed in this resistance is only 5½ kW; and as it is only in circuit for a few minutes per day before the train lights are switched on, its effect on the total efficiency is negligible, and a good deal less than would be the case if the alternative method, namely, separately exciting the interphase transformer with triple-frequency current, had been adopted.

E.H.T. Switchgear. The high-tension switchgear, both in the distribution substation at Wood Green and in the rectifier substations, is of the same type, comprising moulded stone cells with a brick main dividing wall, equipped with spring- and motor-operated circuit-breakers. A two-floor layout is adopted, with the circuit-breakers on the top floor and the bus-bars and instrument transformers below.

As previously mentioned, duplicate auxiliary transformers are provided in the rectifier substations, to furnish the alternating-current supply for the oil circuit-breakers, automatic gear and auxiliaries.

One of these is connected to each incoming feeder, and change-over contactors are included which automatically connect the control bus-bars to the transformer on the incoming feeder which is supplying the substation at any given time. This change-over device is so adjusted that it is possible to transfer the entire load of the substation from one feeder to the other without the slightest interruption of the outgoing services.

A similar arrangement is provided in the distribution substation, except that in this case the auxiliary transformers are incorporated with the potential transformers on the incoming feeders. Similar change-over contactors are provided, which, in the event of the 50-cycle supply being interrupted, automatically transfer part of the control of the rectifier substations to a standby 33⅓-cycle supply, thus enabling the breakers to be opened from the control room even though the rectifiers are out of service.

The high-tension circuits are controlled by means of a modified form of the BTH. spring and motor-operated oil circuit-breaker, Type OH 22. This design of breaker lends itself to the layout described above, in which the breakers are kept on a separate floor apart from the rest of the switchgear; and as only a small quantity of oil is required, fire risks are reduced to a minimum. Phase separation is maintained between the contacts of the oil circuit-breaker.

The operation of this breaker is started by means of a shunt trip coil. This releases springs which in turn operate the breaker contacts for the major portion of the stroke. Towards the end of the stroke an electric motor is switched into circuit and winds up the springs ready for the next operation, at the same time completing the stroke of the breaker contacts. The closing and opening operations are similar, the cycle of operations being started in each case by the shunt trip coil.

The shunt trip is energized from a small nickel-iron battery, which is continuously trickle-charged from a metal rectifier. The design of the breaker is such that even if the motor fails to complete the stroke, the circuit will be broken by the action of the springs alone. For the closing cycle, however, an interlock is provided to interrupt the shunt trip coil circuit should the alternating-current supply fail, thus preventing the possibility of a breaker being damaged by failure to complete the closing stroke.

The motor is of the single-phase series type, operated from the 220-volt control transformer referred to above. This motor is automatically connected in and out of circuit by means of auxiliary switches, the energy being transmitted to the switch mechanism through an electric clutch operated by rectified alternating current obtained from the auxiliary transformer through a copper-oxide rectifier.

The high-tension feeders are equipped with inverse definite minimum over-current relays at the supply ends of the feeders, for giving protection against overloads and earth faults, whilst at the substation ends directional over-current relays are provided.

The arrangement is such that in the event of a fault, both ends of the feeder are cleared without disturbing the sound parallel feeders, thus guarding against a complete shut-down.

Direct-current Switchgear. The output from each rectifier is taken through a reverse tripping high-speed breaker and a negative contactor, on the same floor as the high-tension circuit breakers, to direct-current bus-bars mounted behind a brick wall which separates all bus-bars from the remainder of the substation plant. The necessary isolating switches—both for these circuits and for the outgoing track and escalator feeders—are carried on slate panels mounted in openings in the wall, and are arranged for operation from the side opposite to the bus-bars. The latter rest on Sindanyo slabs carried in stone barriers, with a special clamping device to permit of expansion whilst holding the bars firmly in position.

The track feeders are provided with a forward tripping high-speed breaker on the positive, and a contactor without overload features on the negative; the isolating switches for each pair of feeders are mounted on a single panel, which also carries a cross-over switch enabling two tracks to be fed through a single breaker for short periods when overhauling a breaker becomes necessary. Similar arrangements are provided for the escalator feeders, which, however, are protected by overload contactors in place of the high-speed circuit-breakers used for the tracks.

Remote Control System. In line with previous Underground Railway practice, the remote control system adopted is of the direct pilot-cable type, but it differs from earlier installations in that alternating current is used, the supply being taken from the special dual-purpose control transformers in the Wood Green distribution substation, to which reference has already been made. This alternating-current supply is used to operate small pilot contactors in the substations, the power for the actual operation of the various circuit-breakers being taken from the local control transformer, or, in the case of low-tension circuits such as tracks, escalators, lighting, and signals, from the appropriate local bus-bars.

The central control board (Fig. 193) is of semi-elliptical form, and is divided into nine sections, one for each rectifier substation and two for the incoming high-tension feeders.

From this board the entire power output for the new line is normally controlled, although local operation of the rectifier substation is arranged for should the necessity arise. A drum type control switch with red and green indicating lamps is provided for each circuit to be controlled, whilst continuous indications are given of the current in each high-tension feeder, direct-current amperes and volts on each rectifier, and the air pressure in those substations where compressors are installed.

Each control switch is fitted with a separately operated rotary type switch for controlling an alarm bell; and mounted immediately above it is a drop-shutter relay of the telephone annunciator type. The opening or closing of a circuit-breaker, whether automatically or by operation of the control switch, causes the lamps to change colour and the alarm bell to ring, the latter continuing to sound until disconnected by means of the rotary switch already mentioned. Should the tripping of the circuit-breaker have taken place automatically through the functioning of some protective device, the drop shutter relay is also operated, thus enabling the attendant to see at a glance which particular breaker has functioned.

Particular interest attaches to the panels for the control of the track feeders, which are provided with specially designed control switches and carry a white indicating lamp in addition to the usual red and green lamps. Normal operation is as described above for other circuits, the special features being part of an arrangement whereby the driver of a train or other duly authorized person can, in cases of emergency, completely disconnect the section of track on which he happens to be. Provision for this is made throughout the Underground Railway system, and the arrangement in use on the new extension has been designed to resemble, in its operation, the scheme already employed in the manual substations. Mounted on insulators on the wall of the tunnel within reach of the train driver are two bare copper conductors so spaced that they can readily be brought into contact by pinching them together. The effect of this is to trip the track breaker at each end of the section concerned, whereupon a telephone can be connected to

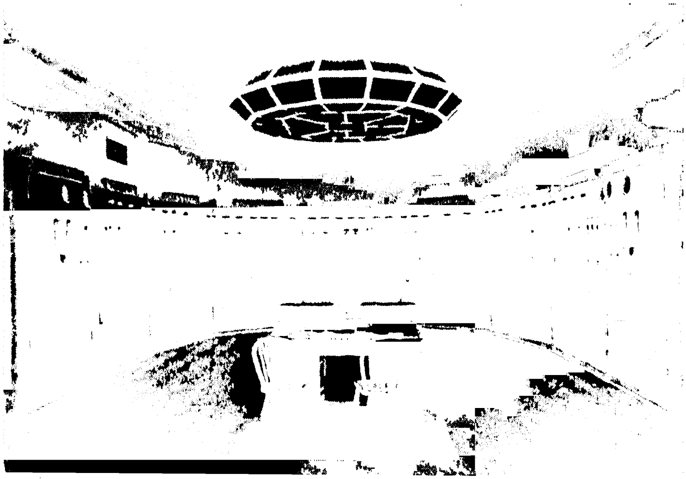


FIG. 193. MAIN CONTROL SWITCHBOARD
British Thomson-Houston Co., Ltd.

the conductors and the occurrence reported to the substation operator.

The bringing together of the two conductors operates a 24-volt relay incorporated in the track control switch at Wood Green, with the following results: The relay trips the track breaker, causing the red and green lamp indicator to change colour, lighting up the white lamp, and ringing the alarm bell; at the same time it releases a spring-loaded plunger carrying a white knob at its forward end. The plunger consequently travels forward through an opening in the escutcheon of the control switch, lifting a gravity-controlled shutter which normally covers this opening, and causing the white knob to be prominently displayed. The forward motion of the plunger automatically locks the control switch in the neutral position, preventing the attendant in the control room from reclosing the breaker without deliberately depressing the plunger and thus resetting the relay. Should only one track open, the control room attendant is warned by the flickering of the red lamp that the track is still alive from the adjacent substation. This flickering continues until the second breaker is opened, thus completely disconnecting the section of track concerned, whereupon the usual green lamp indication is given on both breakers.

Auxiliaries. In addition to the main equipment already described, each substation contains a lighting equipment, comprising a bank of three single-phase air blast transformers with motor-driven blower, and a contactor-type low-tension distribution switchboard arranged for remote control. The transformers are arranged to give a low-tension supply of 440 volts, three-phase, four-wire for substation, railway station, and tunnel lighting, in addition to supplying the motors of the air compressors which are installed at Wood Green, Southgate, and Cockfosters. In all cases, except at Manor House, the capacity of these transformers is 300 kVA, those at this substation being of 450 kVA.

A standby manually-operated lighting equipment of 300 kVA capacity is provided in each substation. This equipment is fed at 33⅓ cycles from the Railway Company's own power station at Lots Road, and the lighting both in the substations and in the tunnels is divided equally between the two sources of supply.

Similar equipment is provided, in all substations except Arnos Grove, for operating the signals, the transformers in this case being naturally air-cooled 50-kVA units, giving a single-phase supply at 650 volts.

As already mentioned, certain substations are equipped with air compressors which feed pipe lines run alongside the track for the operation of points, etc. These compressors are of a type developed specially for the Railway Company by Messrs. Alley & MacLellan, Ltd., some years ago, and standardized for use throughout the system.

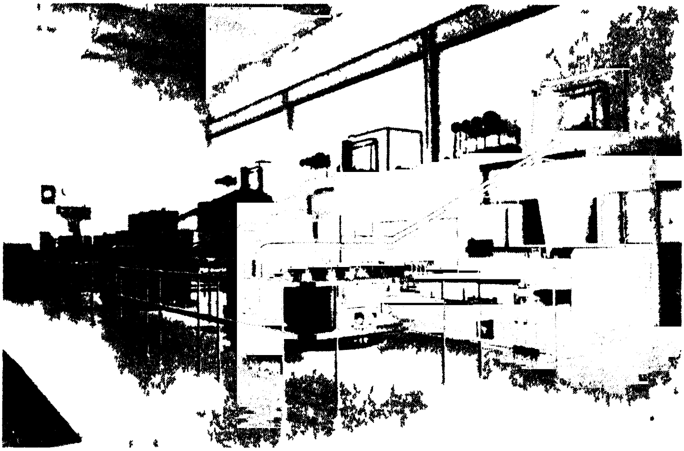


FIG. 194. RECTIFIER UNITS FOR MANOR HOUSE SUBSTATION
British Thomson-Houston Co, Ltd

Substation Layout. The layout of the plant in the substations, which was designed by the London Electric Railway Co. in collaboration with the contractors, has been made uniform in all the substations on the Cockfosters extension, and has also been adopted in other recent rectifier substations on the system. The general arrangement is shown in Figs. 194, 195, and 196.

The first impression gained on entering these substations is one of neatness and spaciousness. The substations have purposely been made somewhat roomy, as in this way air entering from outside can be reduced to a minimum, so that dust will be almost excluded from the substations. While no attempt has been made to squeeze the apparatus into the smallest possible space, the open appearance of the substation is due mainly to careful layout, resulting in simplified connections and avoidance of cross-overs. The location of the rectifier adjacent to the main transformers enables the anode leads, which have to be well insulated and designed for fairly heavy currents, to be neatly arranged in the form of simple copper strips from the transformer terminals to the anode terminals on the rectifier, all cable connections to the anodes being thus eliminated.

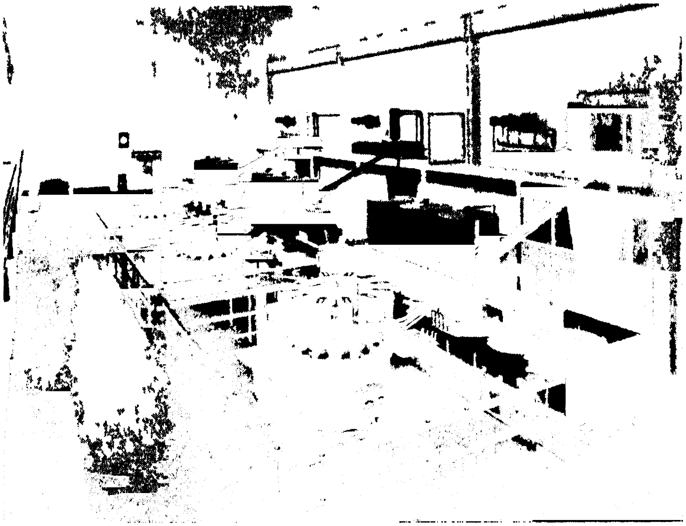


FIG. 195. GENERAL VIEW OF MACHINE ROOM, MANOR HOUSE SUBSTATION
British Thomson Houston Co, Ltd

Again, the position of the cooling equipment economizes in floor space and gives a simpler arrangement of the water pipes, as may be seen in Fig. 195.

The ignition and excitation apparatus, and the insulating transformer for supplying the rotary pump motor, are placed adjacent to the rectifier. All the connections on the secondary sides of these transformers, which are at the full direct-current positive potential to earth, are thus reduced to a length of only a few feet, and a similar simplification results from the mounting of the Pirani gauge panel on the rectifier. It will be appreciated that this feature leads to a clean and dependable layout of the auxiliary wiring between these items and the control panel.

The position of these auxiliaries also enables them to be enclosed inside the same railings as the rectifier, so that almost the whole of the apparatus at full direct-current positive potential is within a single enclosure.

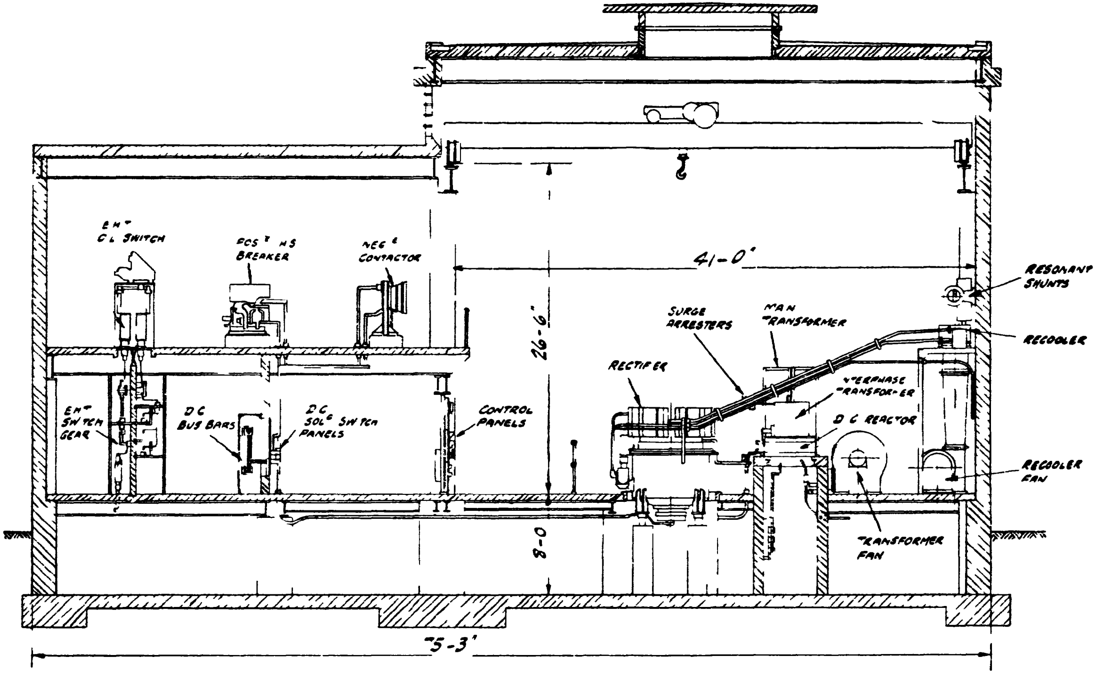
The use of metal screens round the apparatus, which would block the view and collect dust, is avoided in favour of simple open handrails, spaced at a sufficient distance to make unintentional contact with the apparatus impossible. The stanchions supporting the handrails are easily removable from the floor sockets, and the rails are made of wood so as to reduce to a minimum the risk of short-circuiting any apparatus when removing sections of rail.

As may be seen from Fig. 196, the direct-current isolating switches are placed on a wall, the other side of which carries the direct-current bus-bars. This enables these switches to be placed in the direct run of the cables to the circuit-breakers on the gallery above, thus rendering the main connections short and neat. Similarly, the location of the oil switches directly above the alternating-current bus-bar chambers simplifies the layout of the high tension connections.

A simplified diagram of connections typical of BTH. rectifier practice is shown in Fig. 197.

The western extensions of the London Electric Railway, involving the continuation of the Piccadilly Line from Hammersmith to Hounslow and South Harrow, are similarly served by five mercury-arc rectifier substations situated at Sudbury Hill, Alperton, North Ealing, Northfields and Chiswick Park. The contract for the complete equipment of these substations, comprising thirteen 1 500 kW steel-tank rectifiers, together with remote control gear, high and tow-tension switchgear, was placed with the General Electric Co.

For the operation of this extension, power is supplied at 11 000 volts, three-phase, 33⅓ cycles, to a main distribution station at Alperton (adjacent to the substation) by means of four cable feeders from the Neasden generating station of the Metropolitan Railway. As the frequency is the same as that at Lots Road, the possibility of providing an alternative supply has not been overlooked in the general scheme of high-tension connections.



SECTIONAL ELEVATION OF SUBSTATION

FIG 196 GENERAL ARRANGEMENT OF RECTIFIER SUBSTATION
British Thomson-Houston Co, Ltd

Converting Substations. The alternating-current power supply is converted to 630-volt direct current at the four substations at Sudbury Hill, Alperton, North Ealing and Northfields, each of which is connected by two high-tension, parallel cable feeders to the Alperton distribution station. These substations are normally unattended and, in fact, are controlled

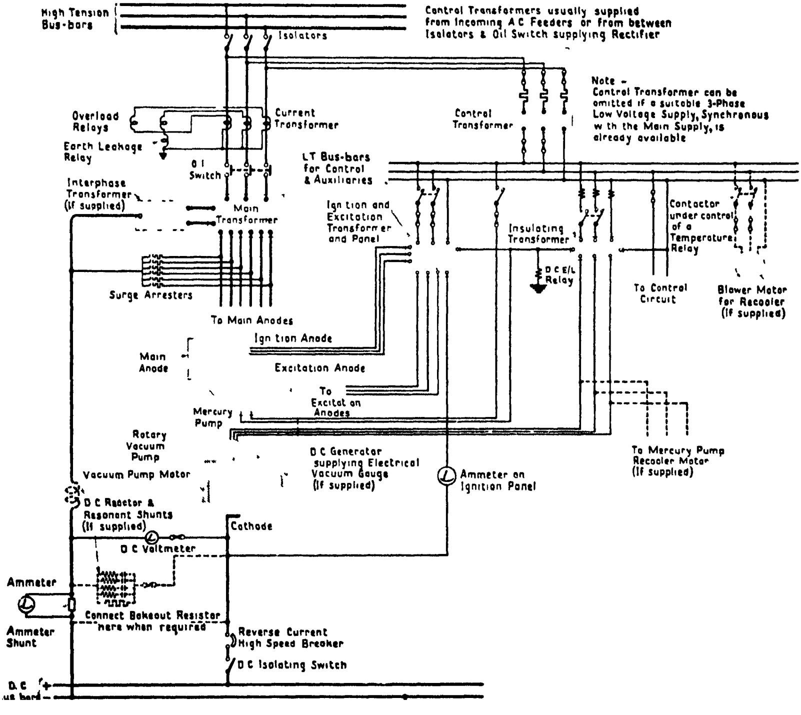

High Tension Bus-bars
Isolators
Control Transformers usually supplied from Incoming A C Feeders or from between Isolators & Oil Switch supplying Rectifier
Note - Control Transformer can be omitted if a suitable 3-Phase Low Voltage Supply, Synchronous with the Main Supply, is already available
Overload Relays
Current Transformer
Control Transformer
Earth Leakage Relay
O I Switch
LT Bus-bars for Control & Auxiliaries
Interphase Transformer (if supplied)
Main Transformer
Ignition and Excitation Transformer and Panel
Insulating Transformer
Contactor under control of a Temperature Relay
D C E/L Relay
Surge Arresters
To Main Anodes
To Control Circuit
Blower Motor for Recooler (if supplied)
Ignition Anode
Main Anode
Excitation Anode
To Excitation Anodes
Mercury Pump
Rotary Vacuum Pump
D C Generator supplying Electrical Vacuum Gauge (if supplied)
Ammeter on Ignition Panel
To Mercury Pump Recooler Motor (if supplied)
Vacuum Pump Motor
D C Reactor & Resonant Shunts (if supplied)
Cathode
D C Voltmeter
Ammeter
Connect Bakeout Resistor here when required
Ammeter Shunt
Reverse Current High Speed Breaker
D C Isolating Switch
D C Bus-bars
+
−

FIG. 197. TYPICAL DIAGRAM OF CONNECTIONS OF RECTIFIER UNIT
British Thomson-Houston Co., Ltd.

from the Alperton Station, which is not only fully equipped for supplying power to, and controlling the four substations mentioned, but is also provided with skeleton equipment for two further substations. A view of the control board at the Alperton distribution station is given in Fig. 203. The fifth substation included in the contract is at Chiswick Park, and is separately fed and controlled from the Ravenscourt Park distributing station.

The thirteen rectifiers are distributed among the five substations as follows—

Sudbury Hill	2
Alperton	2
North Ealing	3
Northfields	3
Chiswick Park	3

The substations are all designed to accommodate three 2 500 kW rectifier units each, although at present 1 500 kW sets are installed.

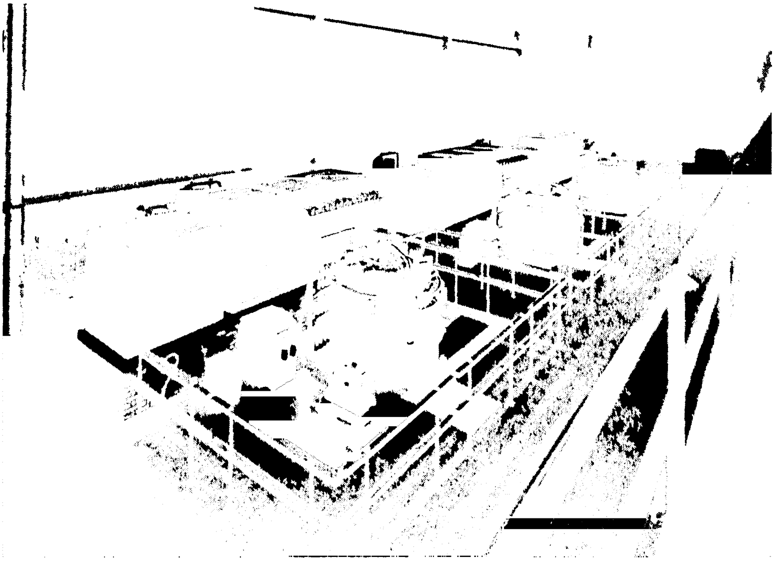


Fig 198. General View of Machine Room, Chiswick Park Substation

General Electric Co

All the rectifiers are identical in design and a similar layout of the equipment has been adopted for all five substations. The Chiswick Park substation is situated in Hardwick Road, close to the railway station, and consists of a spacious rectangular brick building provided with a wide gallery running along the full length of the station. Three mercury-arc rectifiers (Fig. 198) are installed on the ground floor together with their air-cooled transformers, re-coolers for the rectifier cooling water, smoothing reactors, the various control boards, oil circuit-breaker cubicles, isolating switches, and direct-current bus-bars. On the gallery are situated the high-speed circuit-breakers, negative contactors, operating transformers, and high-tension bus-bar chambers.

Rectifiers. The mercury-arc rectifiers (Fig. 199) are of the usual top-plate type, i.e. a circular top plate bolted to the main tank carries the main and auxiliary anodes, condensation cylinder, ignition solenoid, etc. Each rectifier has twelve anodes and these are connected to the secondaries of three single-phase transformers arranged to form a bank providing parallel double three-phase connection. The primary of the transformer is fed from an 11 000-volt three-phase 33⅓-cycle supply. To meet the requirements of the Railway Company the transformers are of the air-blast type, in which a sufficient quantity of cooling air is forced through and round the windings of the transformer by means of a fan. In order to avoid unnecessary complication of the main transformers, which already have a large number of connections, a separate portable baking-out transformer and resistance are provided, thus enabling any

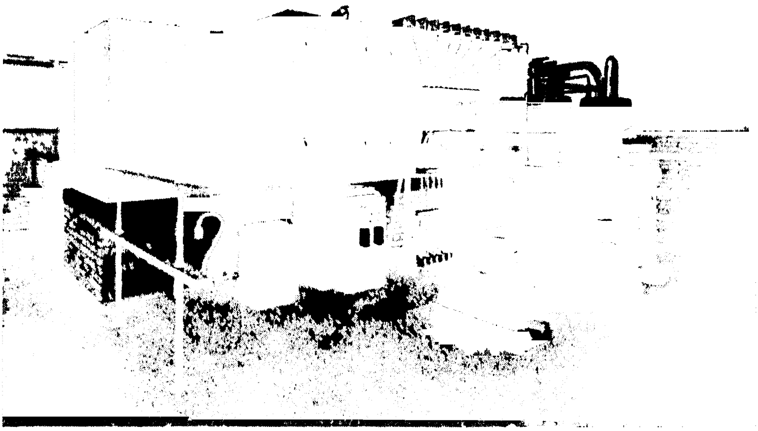


FIG. 199. ONE OF THE THREE 1 500-kW MERCURY-ARC RECTIFIER EQUIPMENTS IN CHISWICK PARK SUBSTATION

General Electric Co.

rectifier unit to be baked out after overhauling, so driving off any traces of occluded gas.

Each anode seal, which is of the vitreous enamel type, is assembled with the anode before mounting on the top-plate, and the joint between the latter and the seal consists of a plain metal-to-metal joint that enables a perfectly air-tight fit to be obtained. Moreover, should it be necessary to open up the rectifier for inspection, all that is necessary is to unscrew the top-plate bolts, after which the whole top-plate can be removed as a unit and every part of the rectifier is readily accessible. An important point is the simple and effective seal provided between top-plate and tank which is obtained without the use of mercury, and can easily be re-made after dismantling.

Much attention has been given to the question of cold starting. It is well known that with early forms of mercury-arc rectifiers great difficulties were experienced in starting from cold, especially when they had to deal with heavy loads. It is now possible, however, to switch on very large loads with the rectifier at ordinary room temperature.

Owing, however, to the necessity for ensuring continuity of service under all conditions, it was decided to provide internal tank heaters, especially as it was understood that no means of heating the substations themselves would be installed. The tank heater is therefore set to operate automatically at 5° C. It is of interest to note, in passing, that cold starting difficulties have been found to be much more pronounced with frequencies of 33⅓ cycles per second than with the standard frequency of 50 cycles per second.

A starting anode is incorporated and is actuated by a solenoid which dips the starting anode into the mercury pool. The starting anode is connected to a direct-current supply obtained from a small motor generator set and carries a current of 5 A. To start up the rectifier, the main oil circuit-breaker is closed, thus energizing the rectifier transformer which in turn energizes the main anodes. The starting anode then operates as mentioned above. As soon as the starting anode is withdrawn from the mercury pool an arc is formed, which is immediately transferred to the auxiliary anodes and in turn to the main anodes.

Auxiliaries. The cooling of the rectifier is effected by water jackets, which are easily removable. The cooling water is circulated by a centrifugal pump through an air cooler and enters at the bottom of the rectifier, flows round the mercury pool, up through a jacket round the main tank, and thence through ducts cut in the top-plate to the condensing chamber and back to the cooler.

The condition of the vacuum in a rectifier is of the greatest importance, and it is necessary to keep the working pressure below 0·01 mm. of mercury, the normal working pressure being 0·001 mm. The vacuum is obtained in two stages, the first stage consisting of a mercury diffusion pump which operates in a manner similar to a steam ejector, while the second stage comprises an oil-immersed rotary box pump and is driven by a small motor off the 230-volt auxiliary alternating-current supply. The usual practice of operating the diffusion pump continuously has been adopted, but as it was not considered good practice to run the rotary pump continuously, the diffusion pump is arranged to feed into an interstage reservoir which is provided with a manometer gauge automatically controlling the starting and stopping of the rotary pump. The latter is automatically started when the pressure in the interstage reservoir reaches a certain pre-determined value, and is stopped when the reservoir is exhausted. It has been found with this system that after the rectifier has been in service a short time it is not necessary to run the rotary pump for a period exceeding 10 min. per day.

In addition to the manometer gauge mounted on the interstage reservoir, a special type of Pirani gauge is inserted in the main evacuating pipe from the rectifier. This gauge has been developed in the research laboratories of the General Electric Co. and is claimed to present certain advantages over other gauges as to the direct and instantaneous indication of pressure on a scale calibrated in microns (mercury head in one-thousandths of a millimetre) and the simplicity with which automatic control is made possible. The action of the gauge depends on the relative cooling of current-carrying metal filaments enclosed in pairs in two separate glass vessels, one of which is evacuated and permanently sealed, while the other is open to the rectifier. These filaments form two arms of a Wheatstone bridge.

A feature of the General Electric type of Pirani gauge is the elimination of the battery which has hitherto been necessary to supply the "hot wire" gauge with low-tension current. The use of this battery is most undesirable, as it demands either an automatic-charging device to maintain its correct voltage or has frequently to be adjusted, as all hot wire vacuum gauges are very sensitive to the exact value of heating current.

The vacuum gauge is supplied with current by a special unit containing a small transformer and a metal rectifier. The constancy of the secondary voltage of the unit may be judged from the fact that were the supply voltage to vary within such wide limits as plus or minus 25 per cent, the secondary voltage, from which the vacuum gauge is fed, would not vary more than plus or minus 0·5 per cent. Moreover, the unit requires no attention.

The diffusion pump is energized by a heater which consumes approximately 1 kW. As this pump is continuously in operation, the rectifier is ready for immediate operation at all times. The heater boils mercury, the vapour of which is discharged through nozzles, at which point air is picked up in the vapour stream and delivered into the interstage reservoir. The mercury vapour is separated from the air in the water-cooled condensing chamber and the liquid mercury returned to the boiling chamber.

A current relay is connected in series with the diffusion pump heater, and this relay prevents operation of the rectifier if the diffusion pump is not working, while a mercury non-return valve is fitted to the interstage reservoir which seals the reservoir from the atmosphere when the rotary pump has shut down.

A small transformer is provided for each rectifier to supply power for the ignition anodes and for heating the mercury diffusion pump, while the motor auxiliaries are supplied from operating transformers, two of which are installed in each substation.

Control Gear. The various control boards are mounted under the gallery and may be seen in Figs. 200 and 201. In the foreground of Fig. 200 is seen the rectifier relay board, and to the right the control board for eight track feeders and the switchboard for operating the oil circuit-breakers controlling the incoming 11 000-volt supply to the rectifiers, various auxiliary transformers, etc. There are also two other control boards, one for track signalling purposes (seen to the right of Fig. 201), and the other for controlling lighting and compressor supplies and the feeders from the 650-volt bus-bars.

Immediately behind the control boards, on a brick wall, are

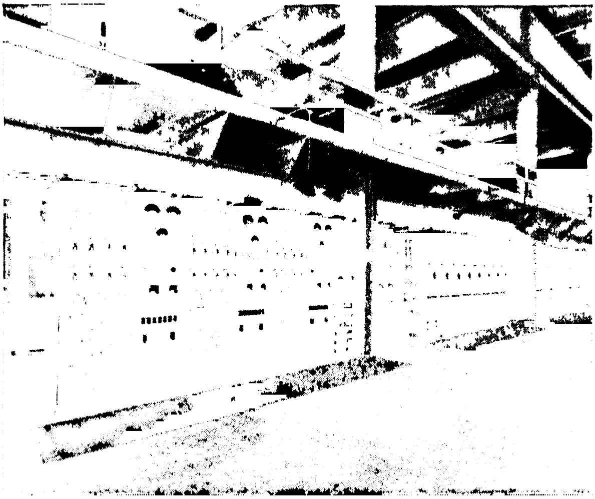


FIG 200 RECTIFIER CONTROL PANEL, TRACK FEEDER PANELS, AND E H T CONTROL BOARDS

General Electric Co

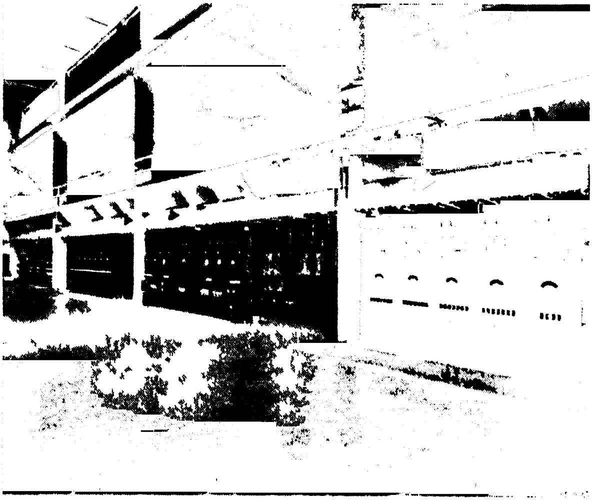


FIG. 201. GENERAL VIEW OF CONTROL BOARDS IN CHISWICK PARK SUBSTATION

General Electric Co.

mounted the direct-current isolating links (Fig. 202), while behind the brick wall are the direct-current bus-bars, at the back of which are the stonework oil circuit-breaker cubicles. Each rectifier is arranged as an automatic unit, so that when the high-tension breaker is closed the rectifier control equipment operates step by step and automatically switches the rectifiers on to the station bus-bars. The rectifiers are protected against all faults by a comprehensive protective system. Each track feeder is connected to the station bus-bars by a positive high-speed circuit-breaker and a negative contactor which provide protection from overloads or short circuits.' The supply for the breakers can be taken either from the bus-bars or the track side of the breaker by means of an automatic change-over contactor, so that the breakers can be closed whether any rectifier in the substation is in operation or not. They may thus be used as tie feeders between the track sections.

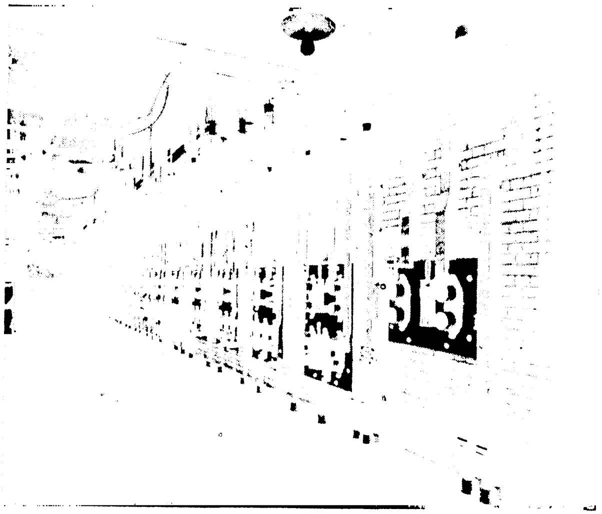


FIG. 202. DIRECT-CURRENT ISOLATING LINKS FOR 1 500-KW RECTIFIERS AND TRACK FEEDERS (CHISWICK PARK SUBSTATION)
General Electric Co.

An auxiliary transformer is connected to each incoming high-tension feeder in each substation as a source of power for closing the oil switches and operating the rectifier auxiliary equipment. The tripping circuits of the high-tension circuit-breakers are energized from an 80-volt battery in each substation which is continuously trickle-charged by means of a metal-oxide rectifier energized from the substation operating supply.

As previously mentioned, four of the substations are under remote control from Alperton distribution station where the remote control board is installed. This board is arranged round three sides of the control room (Fig. 203), separate panels being provided for the control of the incoming feeders and the equipment individual to each substation.

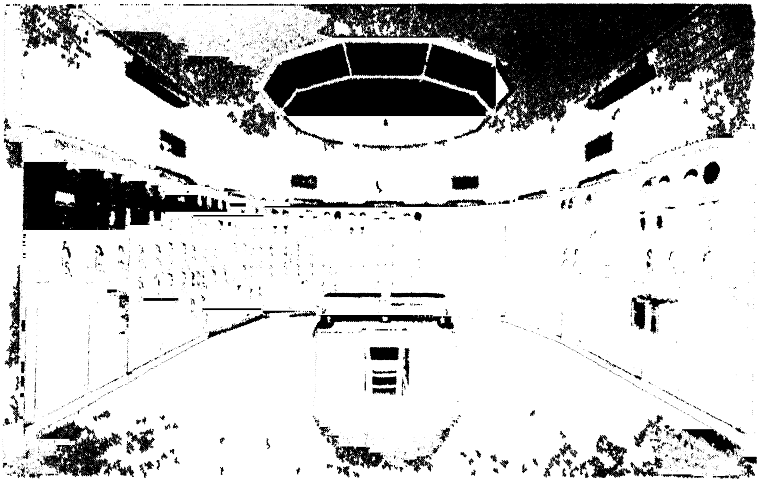


FIG. 203 CONTROL ROOM AT ALPERTON DISTRIBUTION STATION

General Electric Co

For each substation the following remote control facilities are provided—

(*a*) Control of incoming high-tension feeders and continuous indication of switch position.

(*b*) Starting and stopping of each rectifier and continuous indication of oil switch position.

(*c*) Continuous indication of load on each rectifier.

(*d*) Indication of the output of voltage of any one rectifier.

(*e*) Control of track feeders and continuous indication of switch positions.

(*f*) Control of high- and low-tension switches for signalling transformer and continuous indication of switch positions.

(*g*) Control of low-tension circuit-breakers for signalling feeders and continuous indication of switch positions.

(*h*) Control of high- and low-tension switches for railway lighting transformers and continuous indication of switch positions.

(*i*) Control of low-tension circuit-breakers for lighting feeders and continuous indication of switch positions.

(*j*) Control of low-tension circuit-breakers for starting and stopping compressor motors for track signalling purposes.

(*k*) Continuous indication of the air pressure in the compressor reservoirs.

(2) GLASS-BULB RECTIFIER EQUIPMENTS FOR ELECTRIC RAILWAY SERVICE.

Although the steel-tank rectifier is undoubtedly the static convertor *par excellence* for heavy-duty traction supply, especially at high voltage, it must not be thought the glass-bulb rectifier has no application for direct-current supply to electric railways. On the contrary, traction rectifier equipments with glass-bulb rectifier units have been in use on the Continent for some years; in fact, as far back as 1924, the Siemens-Schuckert-Werke supplied a bank of glass-bulb rectifiers to the Schleizer Kleinbahn for its 1 200-volt direct current system at Weimar.* As more recent examples of glass-bulb rectifier equipments for electric railway service on the Continent may be cited the numerous substations put down in 1931 to supply the 600-volt system of the Chemins de Fer Vicinaux in Belgium.

Considerable interest in this country was therefore aroused by the decision of the London Midland and Scottish Railway authorities a few years ago to re-equip several of their substations supplying the Liverpool-Southport and Manchester-Bury lines with glass-bulb rectifiers, notwithstanding the considerable experience already gained with the steel-tank type of mercury-arc rectifier which proved so successful in connection with the recent electrification of the Manchester, South Junction and Altrincham Railway.† The installation comprised four 1 200-kW substations and the contract for their equipment was placed with the Hewittic Electric Co. Two of the substations supply the Liverpool-Southport line at 600 volts, whilst the two remaining substations supply the Manchester-Bury line at 1 200 volts. An interesting feature of these installations is that provision has been made for increasing the substation output to 1 500 kW at a future date by raising the direct-current output pressure to 750 volts and 1 500 volts respectively.

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* As far as the author is aware, this particular installation represents the first application of the mercury-arc rectifier to direct-current railway electrification at high voltage.

† Vide *Journal I.E.E.*, 1933, Vol. 73, pp. 473 *et seq.*

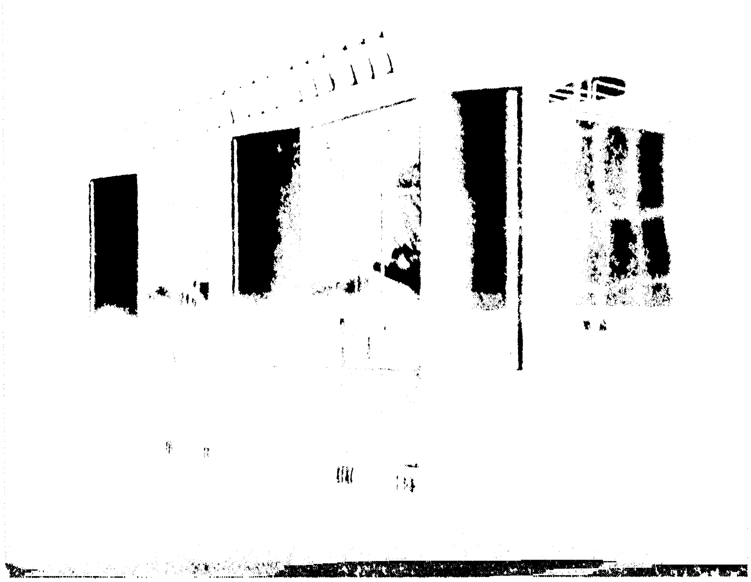


FIG. 204 1 200-KW GLASS-BULB RECTIFIER BANK IN HILLSIDE SUBSTATION

Hewittic Electric Co.

The two 600-volt substations supplying the Liverpool-Southport lines are situated at Hillside and Wicky Dale, and are arranged for remote control from the Southport rotary-convertor substation. Each substation is capable of dealing with the following loads—

1 200 kW, 2 000 A continuously.
1 500 kW, 2 500 A for two hours.
2 400 kW, 4 000 A for ten minutes.
3 600 kW, 6 000 A momentarily.

The converting equipment accordingly consists of eight glass-bulb rectifier units, arranged in two rows of four, placed back to back as illustrated in Fig. 204. The rectifier banks are supplied from outdoor-type oil-cooled transformers connected quadruple three-phase on the secondary side, the transformers in turn being connected to the 7 500-volt three-phase 50-cycle power system through Reyrolle metal-clad oil circuit-breakers.

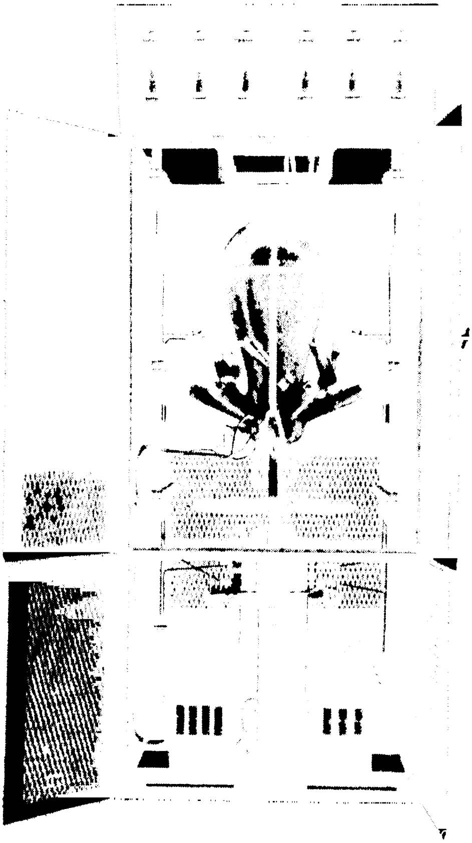


FIG. 205. 250-A GLASS-BULB RECTIFIER UNIT
The Engineer

Each rectifier unit (Fig. 205) is self-contained, with its own auxiliaries and with means for ready isolation, and the bank can be run with any number of units in service. The twelve-phase supply from the transformer is taken direct to two sets of six-phase bus-bars (*cf.* Fig. 209) at the top of the rectifier cubicles. Each individual rectifier, therefore, operates as a six-phase unit, and as many units as are required can be connected to each set of bus-bars. From the latter the supply to each unit is taken first through anode fuses and then through oil-immersed equalizing choke coils which ensure correct load distribution between the rectifier bulbs working in parallel. The fan motors and excitation anodes are supplied from appropriate auxiliary windings on the main transformer.

The rectifier cathodes are connected *via* isolating switches to the positive direct-current bus-bar located at the bottom of the cubicles, and the supply to the track is completed through a reverse-current high-speed circuit-breaker and the track feeder circuit-breakers, which latter are also of the high-speed type, but designed for forward tripping (on overloads). The direct-current switchgear and control gear (Fig. 206) was supplied by Bertram Thomas.

FIG. 206. CONTROL SWITCHGEAR, WICKEY DALE SUBSTATION

The Engineer

At the manually-operated control substation in Southport there are duplicate batteries for the supplying of the remote control apparatus. One battery is in service whilst the other is being charged from the 600-volt mains through a stepped resistance and multi-contact switch. Individual feeder and rectifier control is provided, and complete indication is given of the various operations. For example, when a rectifier bank is shut down this is indicated at the control substation; and, in the same way, indications are given of the feeder circuit-breaker positions. Moreover, the direct-current output voltage and the substation load can be read directly at the control board, whilst an alarm is given in the event either of a circuit-breaker tripping or of failure of a rectifier bulb.

The general layout of these 600-volt rectifier substations may be seen from the plan view given in Fig. 207.

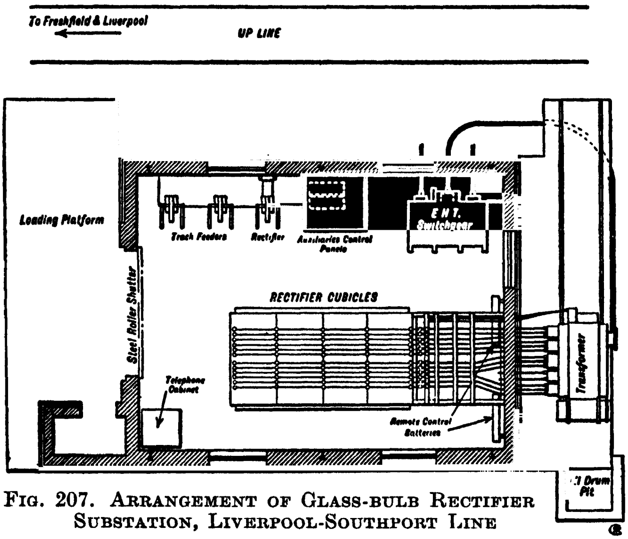


FIG. 207. ARRANGEMENT OF GLASS-BULB RECTIFIER SUBSTATION, LIVERPOOL-SOUTHPORT LINE
The Engineer

The two 1 200-volt substations supplying the Manchester-Bury line installed at Victoria and Radcliffe are similar in arrangement and equipment. Each substation contains three banks of six rectifier units supplied with three-phase alternating current at 50 cycles and 11 000 volts. The total rectifier capacity is thus 7 200 kW, which output is adequate to the demands of the heaviest traffic on the line, so that no other converting plant whatever is employed. The rectifier banks each have the following ratings—

1 200 kW, 1 000 A continuously.
1 500 kW, 1 250 A for two hours.
2 400 kW, 2 000 A for ten minutes.
3 600 kW, 3 000 A momentarily.

The six rectifier units composing each 1 200-kW bank are arranged in two rows of three, face to face, and with a gangway between. On account of the high output voltage in this case, each bank along with its high-speed circuit-breaker is completely enclosed by a grille, the door of which is interlocked with the high-tension oil switch. One-half of a rectifier bank in the Radcliffe substation is illustrated in Fig. 208, whilst the principal connections of the rectifier equipment are shown in the diagram of Fig. 209. The equipments are designed for both manual and electrical operation, whilst the Victoria substation is, in addition, arranged for remote control from the Radcliffe substation.

FIG. 208 ONE HALF OF A 1 200-KW RECTIFIER BANK IN RADCLIFFE SUBSTATION

Hewittic Electric Co

(3) STEEL-BULB RECTIFIER EQUIPMENT FOR TROLLEY-BUS SERVICE

The growth of the trolley-bus service in London during the last few years has necessitated the provision of new substations for supplying electric power. One of the earliest of these is

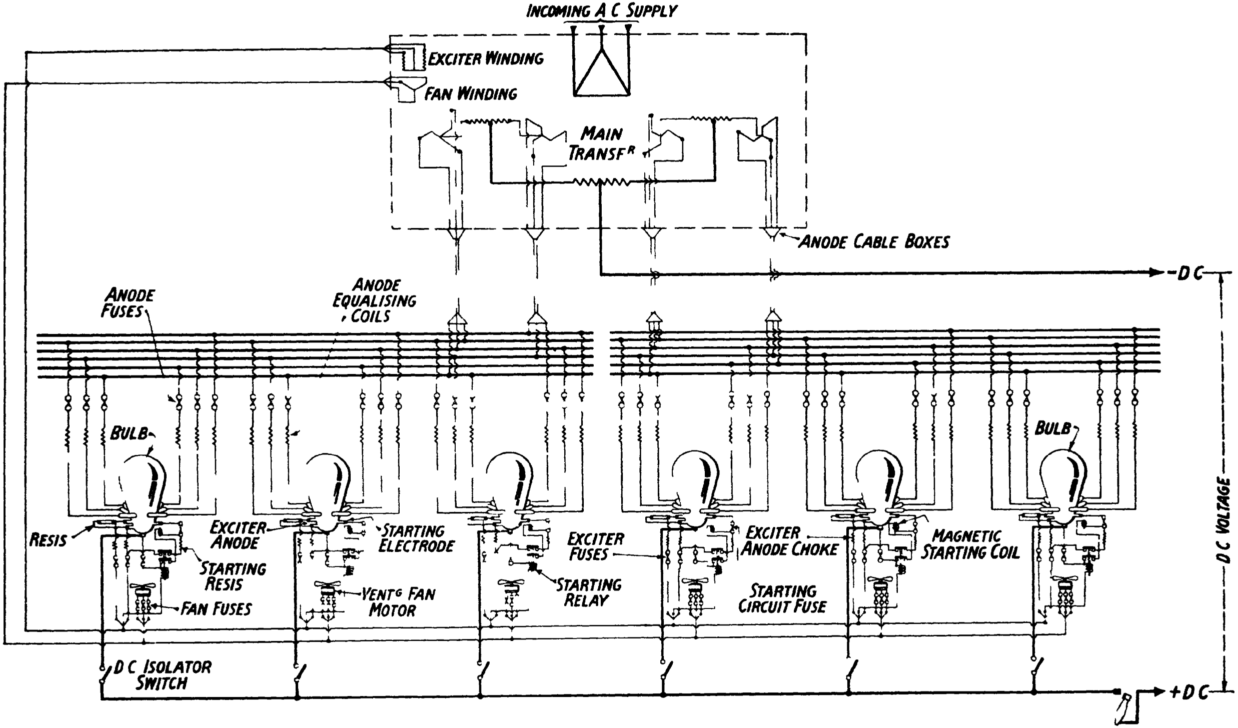


Fig 209 Diagram of Connections for a Rectifier Substation, Manchester–Bury Line

Hewittic Electric Co

situated at Putney Bridge. After careful consideration it was decided by the engineers of the London Passenger Transport Board that the converting equipment in this substation should consist of pumpless air-cooled steel-clad mercury-arc rectifiers, a type of plant recently developed by one of the leading electrical manufacturers in this country.

A most prominent feature of the air-cooled steel-clad rectifier is that the use of pumps is dispensed with, thus affording a self-contained rectifying unit which offers all the advantages of the robust construction associated with steel-clad apparatus: fragile materials such as glass are eliminated. Among other advantages of this type of rectifier should be mentioned high efficiency, ability to carry heavy overloads and withstand short-circuits, and remarkable freedom from back-fires.

The success that has attended the manufacture of the steel-bulb rectifier has been largely due to the patented vitric seal, which is employed by the General Electric Co. for all its steel rectifiers. This seal consists of a number of thin mild-steel cones, which are separately coated with a special vitreous enamel. After assembly the cones, together with the top and bottom members, are fused up solid in an electrically heated oven. The resulting seal has a very high dielectric strength, is perfectly vacuum-tight, and can be secured to the rectifier in the simplest way, all metal-to-metal joints being welded.

For cooling the rectifiers, a patented system of air-cooling has been adopted, which has proved most effective in service and enables the maximum possible output to be obtained from a given size of unit.

There are three of these 250-kW rectifier units installed at Putney Bridge for the supply of power at 600 volts d.c. They are shown in Fig. 210, from which it will be seen that each unit comprises two six-anode rectifiers.

The substation is normally unattended and is remote-controlled from an adjacent railway substation. Provision is also made for emergency remote control of the outgoing d.c. feeders from pillars which are installed at convenient points along the trolley-bus routes, so that in the event of a street accident, power can be cut off quickly from any section of the system should this be necessary.

Power at 11 000 volts, three-phase, 33⅓ cycles, is supplied to the substation through two feeders, one of which supplies one rectifier unit and the other the two rectifiers, which are arranged

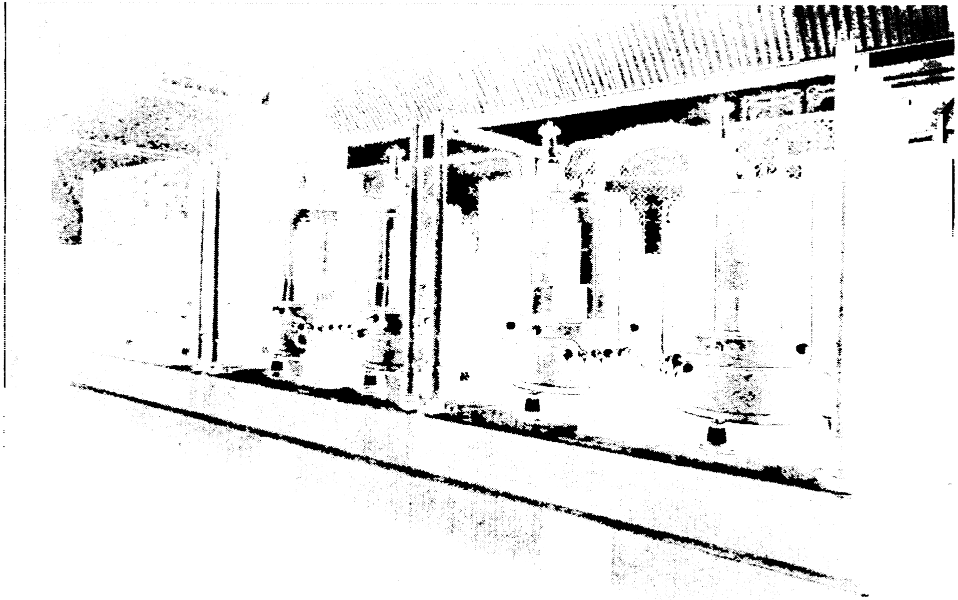


FIG 210 THREE 250 kW 600 VOLT PUMPLESS AIR COOLED STEEL CLAD MERCURY ARC RECTIFIER UNITS AT PUTNEY BRIDGE SUBSTATION*

London Passenger Transport Board

* This was the first installation of steel bulb rectifiers in this country

to operate in parallel. The incoming feeders are connected through isolating links to the primary windings of the main transformers.

The automatic control equipment at the substation is shown in Fig. 211. Provided the incoming high-tension isolating links are closed, it is only necessary to close the oil circuit-breaker at the remote-control station, when the rectifying plant will start up automatically. On operating this switch, the primary of the appropriate main transformer is energized, which in turn supplies power to the small auxiliary transformer. The cooling fans start up immediately, and when an adequate air flow is established the blower relay operates and the rectifier

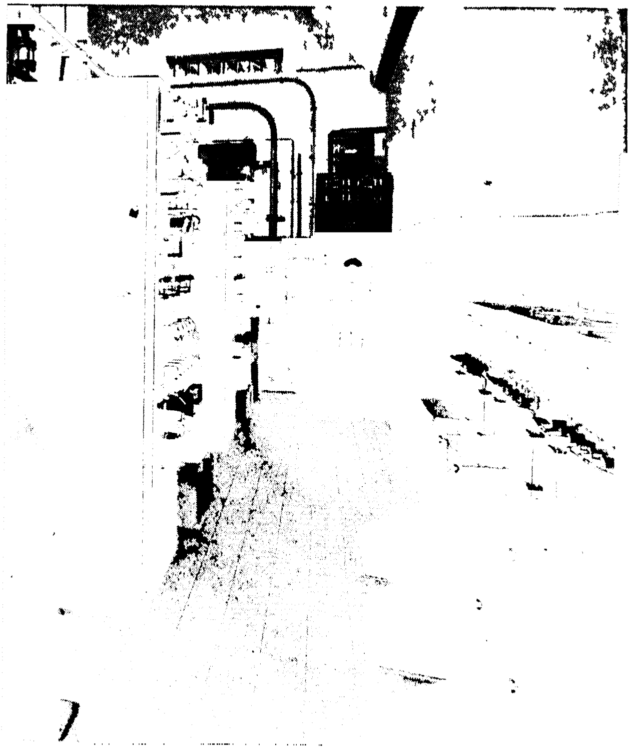


FIG 211. AUTOMATIC CONTROL CUBICLES FOR STARTING UP THE RECTIFIER EQUIPMENT

General Electric Co

ignition and excitation circuits are energized. The rectifier unit is thus brought into service. As soon as a d.c. voltage is established at the rectifier terminals, the reverse-current high-speed circuit-breaker in the positive main closes, and this operation is immediately followed by the closing of the negative contactor, which is gang-controlled with the high-speed breaker. The rectifying plant is thus connected to the bus-bars of the d.c. switchboard. The reverse-current high-speed circuit-breakers are shown in Fig. 213.

FIG. 212. THREE MAIN AIR-BLAST TRANSFORMERS WHICH SUPPLY THE 250-KW RECTIFIER UNITS SHOWN IN FIG. 210

General Electric Co.

To close down a rectifier, the remote-control breaker is tripped. All the control equipment at the substation will reset automatically in readiness for restarting.

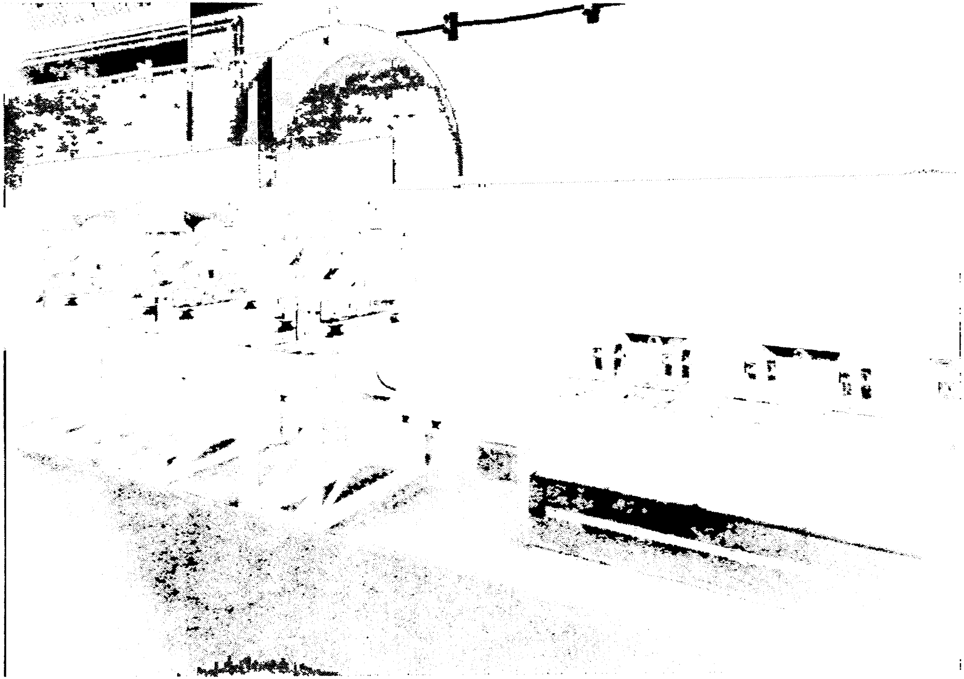


FIG. 213. REVERSE CURRENT HIGH-SPEED CIRCUIT-BREAKERS FOR CONTROLLING THE POSITIVE MAINS FROM THE RECTIFIERS

On the right are shown the series-connected reactors which form part of the smoothing apparatus

General Electric Co

The main d.c. switchboard (Fig. 214) includes three rectifier panels, an output and test panel, six feeder panels, and a B.O.T. panel. This board is so arranged that the total output from the substation is fed through the output and test panel, where it is metered and passes through a summation overload relay to the six feeder panels.

In the event of an overload on the substation, the summation overload relay operates after a predetermined time and trips all feeders simultaneously. Arrangements are also made to trip all feeders when the entire rectifier plant is shut down.

Faults on individual feeders are cleared rapidly and without disturbance to the rest of the system by means of high-speed circuit-breakers, which are mounted above the switchboard. Should a high-speed breaker with its gang-controlled negative contactor open on a fault, an auto-reclose relay is brought into operation, and after a given time again closes the breaker and its contactor. If the fault persists, the auto-reclose relay will lock out after a given number of reclosures have taken place. After the fault has been rectified, the auto-reclose relay can be reset from the remote-control pillars along the trolley-bus routes, so that it is not necessary for an attendant to visit the substation.

For safeguarding the installation against damage from faults on the system or in the rectifying plant itself, the following protective features are provided—

(i) *High-tension Overload and Earth Leakage.* Each of the high-tension circuit-breakers is equipped with double-pole overload and single-pole earth-leakage relays, which trip the breaker in the event of an overload or earth fault in the primary windings of the main transformer and thus shut down the rectifier.

(ii) *Protection Against Overheating of the Rectifier Top Plate.* If, due to continued heavy loads, the rectifier becomes overheated, a thermostat fitted in the rectifier top plate trips the high-speed breaker and isolates the unit until it has cooled down to a safe temperature. The thermostat contacts then operate to close the breaker and restore the load on the rectifier.

(iii) *Failure of Cooling Air.* Blower relays are provided which prevent the rectifier ignition equipment from operating until an adequate flow of cooling air has been established. In the event of failure of the cooling air system when a rectifier is in service, the relays trip the high-speed breakers and switch off the excitation arc.

(iv) *Overloading of the Fan Motors.* If a fan motor becomes overloaded, it is isolated from the supply by means of an overload relay. The resulting failure of the air flow causes the blower relay to operate and shut down the appropriate rectifying unit.

(v) *Protection Against Fire.* In order to minimize fire hazard, thermostats are mounted above the main transformers, and trip the appropriate high-tension oil circuit-breaker in the remote-control station if the heat produced by any of the transformers becomes abnormal.

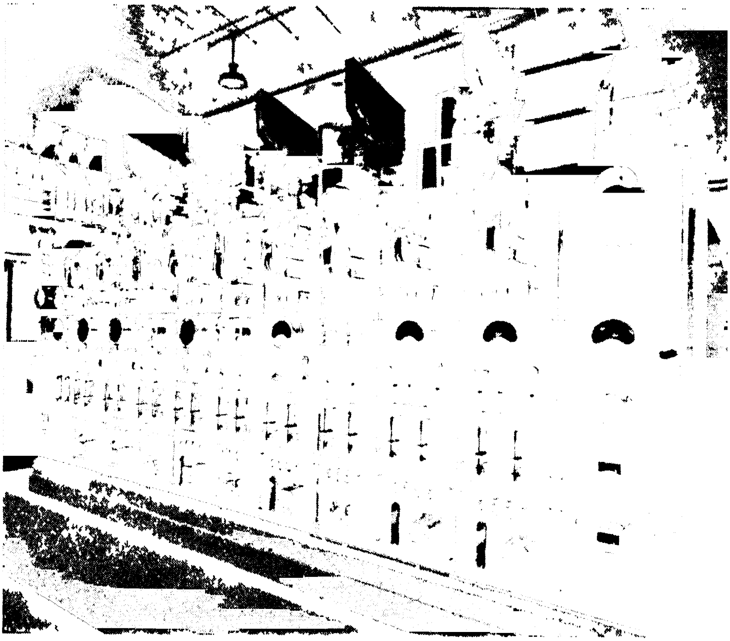


FIG. 214. THE MAIN SWITCHBOARD FOR CONTROLLING THE OUTGOING D.C. SUPPLY FROM THE SUBSTATION

Mounted above the switchboard are the high-speed circuit-breakers for the six feeder circuits

General Electric Co.

The main transformers, which are shown in Fig. 212, embody the three-phase core-type construction and are designed for air-blast cooling. Each transformer is mounted on a brick chamber into which the cooling air is blown by the fan, whence it passes through ducts in the windings and is exhausted through an adjustable baffle embodied in the top of the transformer housing. As each transformer supplies the two rectifying cylinders which form a complete unit, balancing choke coils are provided to ensure equal distribution of the load.

Three small transformers, each of which is energized from the low-tension side of the appropriate main transformer, supply power for all the auxiliary equipment and are designed with three three-phase secondary windings. Two of the windings are completely insulated from earth and supply current for the rectifier ignition and excitation equipment, while the third, one phase of which is earthed, provides power at 230 volts for the cooling fan motors for the main transformers and rectifiers as well as for operating contactors, relays, and so on.

Precautionary measures are adopted for minimizing interference with radio communication services which might occur as a result of ripples in the d.c. output of the rectifier. For this purpose an efficient smoothing apparatus has been installed and includes a series-connected reactor coil for each rectifier cathode and resonant shunt circuits, which are tuned for the principal harmonics in the d.c. output. The series-connected reactors can be seen on the right of Fig. 213.

(4) A Fully-automatic Grid-controlled Steel-tank Rectifier Substation for Municipal Lighting and Power Supply

An outstanding feature of mercury-arc rectifier equipment is the facility with which it can be arranged for automatic working. Unlike rotating converting plant, which has to be run up to speed and synchronized before being switched on to the alternating-current supply, and has then to be paralleled on the direct-current side before being closed on to the substation bus-bars, a rectifier installation can instantly be put on load by merely closing the high-tension circuit-breaker.

In the case of the 500-kW steel-tank rectifier equipment installed at the Stuart Road Substation of the Birkenhead Corporation Electricity Department, the nature of the substation load necessitated a definite over-compounding of the output voltage-characteristic. And of the three principal and alternative ways of meeting this requirement, viz. by on-load tap-changing on the main transformer, by an induction regulator, or by grid control of the rectifier itself, the latter alternative was selected as being not only the most efficient, but also the most naturally suited to meet the further requirement that the amount of over-compounding should be adjustable between the limits of 4 per cent and 8 per cent, the normal figure being 6 per cent. Incidentally, this automatic substation, which was completely equipped by the English Electric Co., is of special interest as being the first of its kind in this country to include grid-control of the direct-current output voltage.

The function of this particular equipment is to assist other substation plant, supplying the base load of the three-wire direct-current system, during times of peak load. Such times are indicated by a fall in voltage at points remote from the main area of supply; so that if additional converting plant situated in such an outlying part of the system is arranged to start up when a low voltage is experienced there, the equipment will come into service automatically at the desired time.

When the load peak has passed, a time comes when the service of the auxiliary plant is no longer necessary, and this condition will be observed by the falling-off in the load on the additional plant; hence the plant is made to shut down when low load occurs.

Almost all systems are subject to momentary fluctuations of load, so that it is generally desirable that short time intervals be introduced between the occurrence of the correct starting or stopping conditions on the system and the actual starting-up or shutting-down of the converting plant, otherwise a number of unnecessary starts and stops are liable to occur. This time-lag feature is incorporated in the equipment to be described.

The rectifier equipment is illustrated in Figs. 215 and 216, whilst the general circuit arrangement of the complete installation can be seen from the key diagram (Fig. 217). The rectifier is supplied from a 780-kVA, six-phase fork-connected transformer, which presents no unusual features, except that special tappings are brought out on the secondary side for providing a low voltage during baking-out. The disposition and method of leading-out the several secondary connections is shown in Fig. 218. The usual lightning type auto-valve arrestors are connected across the individual secondary phases to protect the transformer from voltage surges such as may

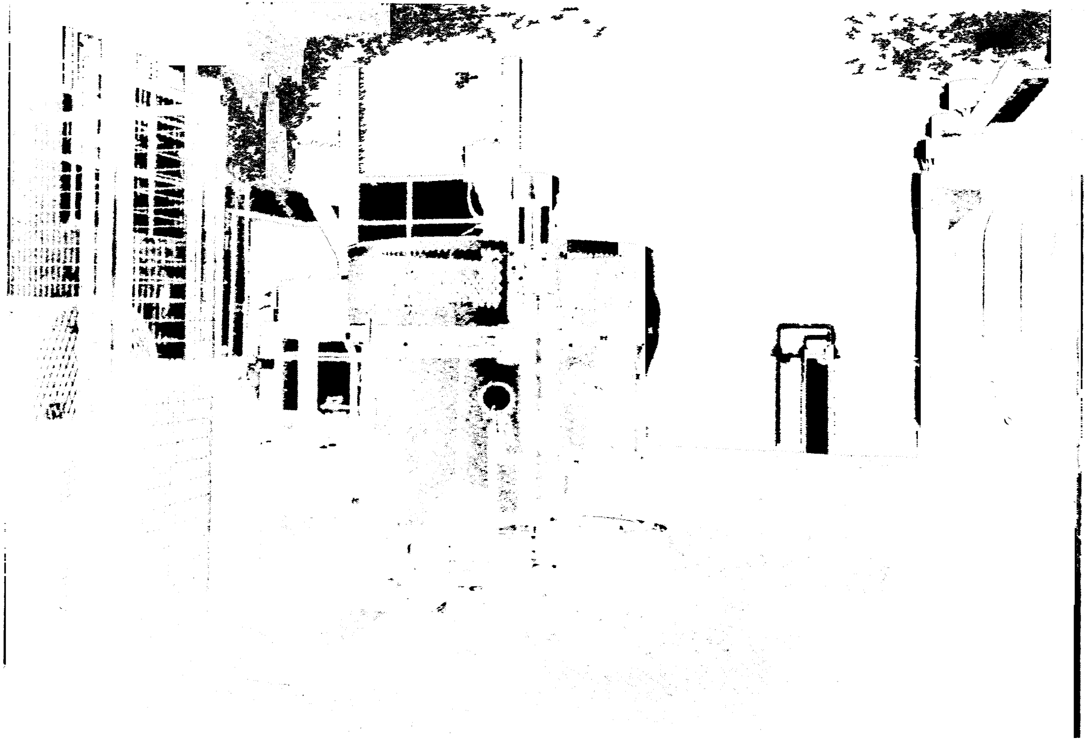


FIG 215. 500 kW FULLY AUTOMATIC STEEL TANK RECTIFIER INSTALLATION
View of rectifier with its transformer and smoothing equipment (in background)
English Electric Co

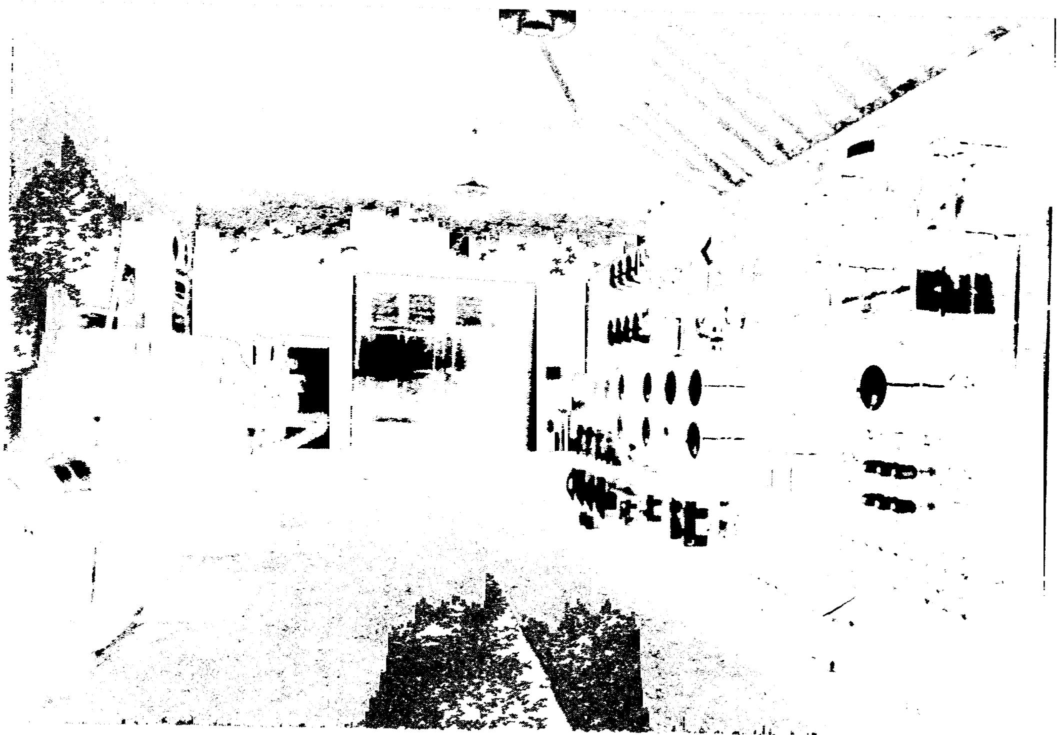


Fig. 216. 500-kW Fully Automatic Steel tank Rectifier Installation

View of alternating-current and direct-current switchgear and control panels

English Electric Co

sometimes occur under conditions of low temperature inside the rectifier. On the primary side the transformer is provided with plus and minus 2½ per cent and 5 per cent tappings, and is connected to the 6 600-volt, three-phase, 50-cycle supply through a standard metal-clad circuit-breaker which includes a solenoid-operated oil switch having a guaranteed safe rupturing capacity of 150 000 kVA, shown in Fig. 219.

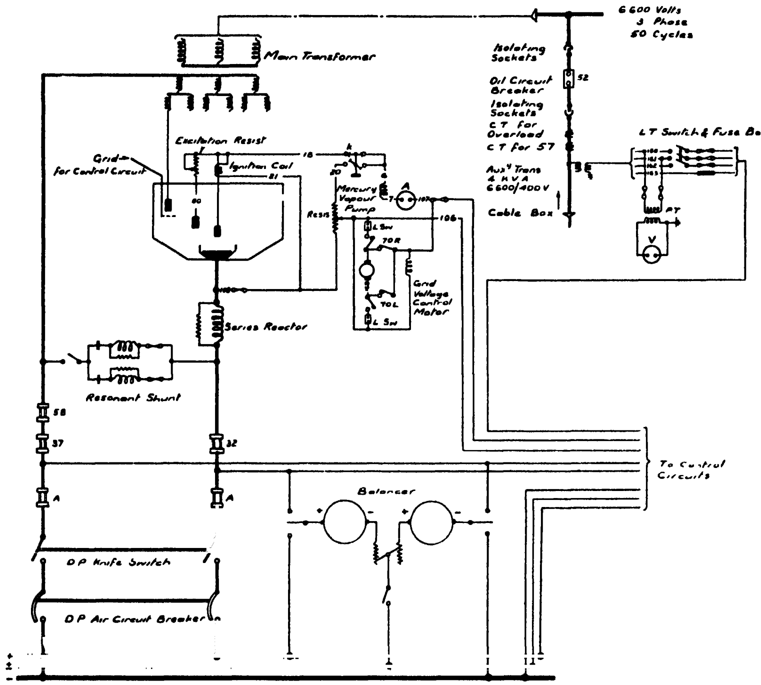


FIG. 217. SIMPLIFIED DIAGRAM OF CONNECTIONS OF THE EQUIPMENT OF FIG. 216

English Electric Co.

The 500-kW steel-tank rectifier is of normal design, and is illustrated in Fig. 220. The outstanding feature of the unit is the provision of special control grids, situated in the arc path immediately below the main anodes. The electrical connections to these grids are brought out to suitable terminal flanges insulated from the anode plate, in the same manner as in the case of the main anode-connections. One such insulated grid connection can be seen in Fig. 220, immediately above the thermometer. The customary vacuum-pumping equipment is provided, incorporating a barometric seal which effectively

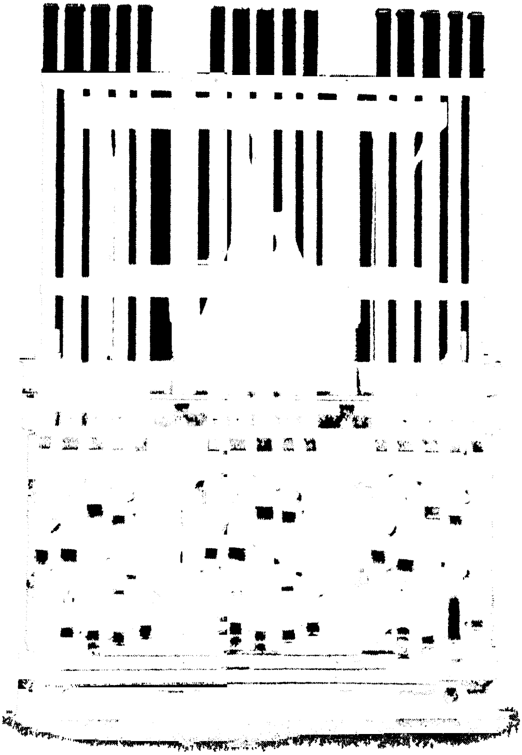


FIG. 218. VIEW OF 780-KVA, SIX PHASE FORK-CONNECTED TRANSFORMER REMOVED FROM TANK
English Electric Co

seals off the rectifier from the atmosphere during the shut-down periods of the rotary vacuum-pump. The main cooling water supply is regulated by means of a thermostatically-operated inlet valve, while that for the mercury-vapour pumps is allowed to flow continuously.

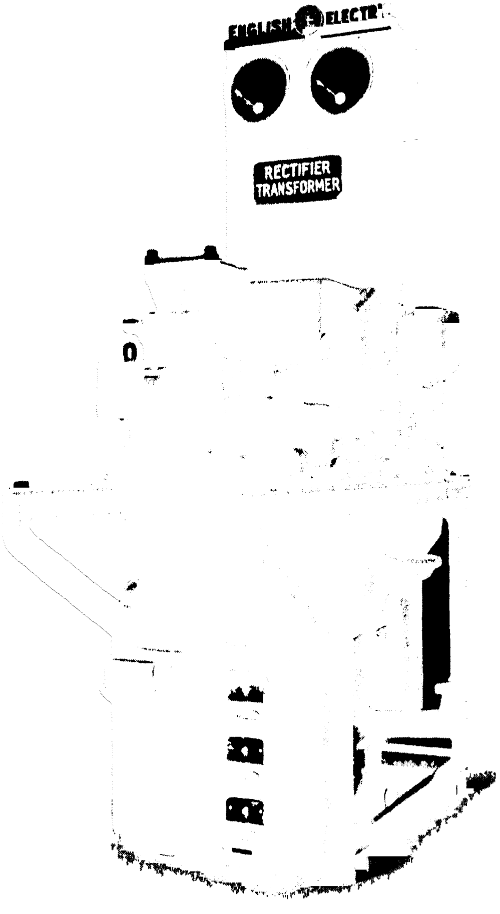


FIG. 219. METAL-CLAD, COMPOUND-FILLED, OIL CIRCUIT-BREAKER
English Electric Co.

The direct-current supply for providing ignition and excitation of the rectifier is obtained from a special rectifying unit of the metal-oxide type, which at the same time serves to supply the small motor operating the contact-making control disc of the grid-excitation equipment.

Grid-control Gear. The grid-excitation system employed for this unit (*vide* Fig. 81) is of the impulse type, giving "hard" control as described in Chapter IX, and comprises the following main components.

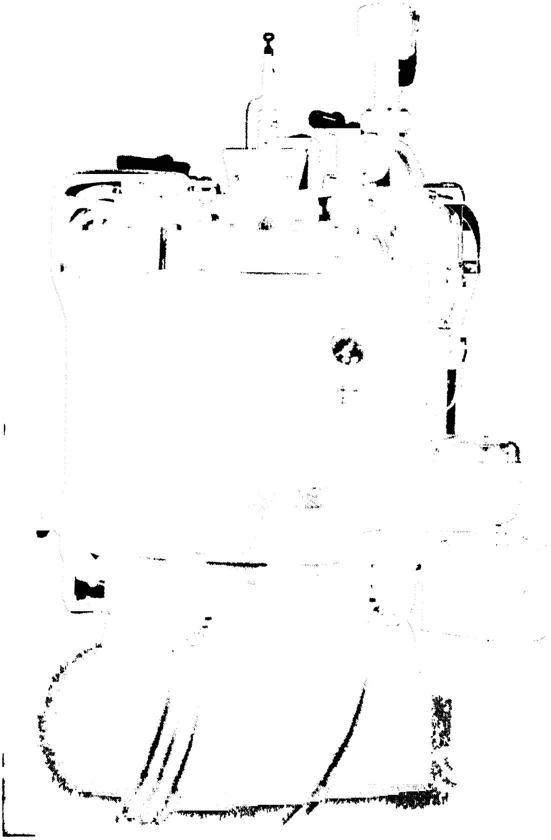


FIG. 220. 1 000-A GRID-CONTROLLED STEEL-TANK RECTIFIER
English Electric Co

(*a*) Synchronous motor with shaft extension carrying the brushgear.

(*b*) A contact disc, carried on a spindle, which can be rotated through a small arc.

(*c*) A direct-current operating motor which drives the disc through double-reduction gearing. This motor is reversible, and is controlled by the voltage-regulating relays.

The synchronous motor is coupled electrically to the same source of alternating-current supply as the supply to the anodes, and therefore runs synchronously with the anode voltage. It has a separately excited field which ensures that it pulls into step with correct phase relationship. The field excitation is supplied from a small metal-oxide type rectifier, which is in turn supplied from a small single-phase transformer fed from the same source as the main three-phase winding of the motor. The motor has actually two fields magnetically in quadrature. By varying the relative strength of the two fields the rotor position relative to the stator flux can be varied. In the present case, however, this feature is not employed, and both fields are kept at a constant excitation.

The brushgear on the synchronous motor shaft rotates over countersunk studs on the insulating contact disc. The contacts on the disc are connected one to each of the control grids, and the brush sweeps uniformly over them. The grids are connected by the brushgear to a source of potential which is positive with respect to the cathode. During the period when the grids are not connected to the positive potential they are maintained negative with respect to the cathode. The studs on the disc, and the rotation of the brushgear, are so arranged that the sequence of the positive impulses is the same as the sequence of firing of the anodes.

As the contact disc can be rocked backwards and forwards, it is clear that the instant at which the grids are made positive can be made later or earlier in the periods during which the respective anodes are positive and tending to fire; and as an anode cannot fire until its grid is made positive, although once started, it will continue to burn even if its grid is made negative. Therefore, if the positive impulse occurs soon enough an anode will fire over the whole of its normal firing period, but if the positive impulse occurs late in the voltage cycle, then the anode will fire only from that time to the end of its normal firing time.

The voltage of a rectifier is the mean of the anode voltages over a complete cycle. This mean value is dependent on the maximum anode voltage, the wave shape, and the firing time, and as the two first conditions are constant and the latter can be varied, the voltage can be altered from the maximum to zero by altering the firing time, which in turn is controlled by the position of the contact disc. Now as the position of the contact disc is controlled *via* the rocking motor and its contactor gear from the voltage-regulating relay, the rectifier voltage can be made to vary as required in accordance with the voltage-regulating relay.

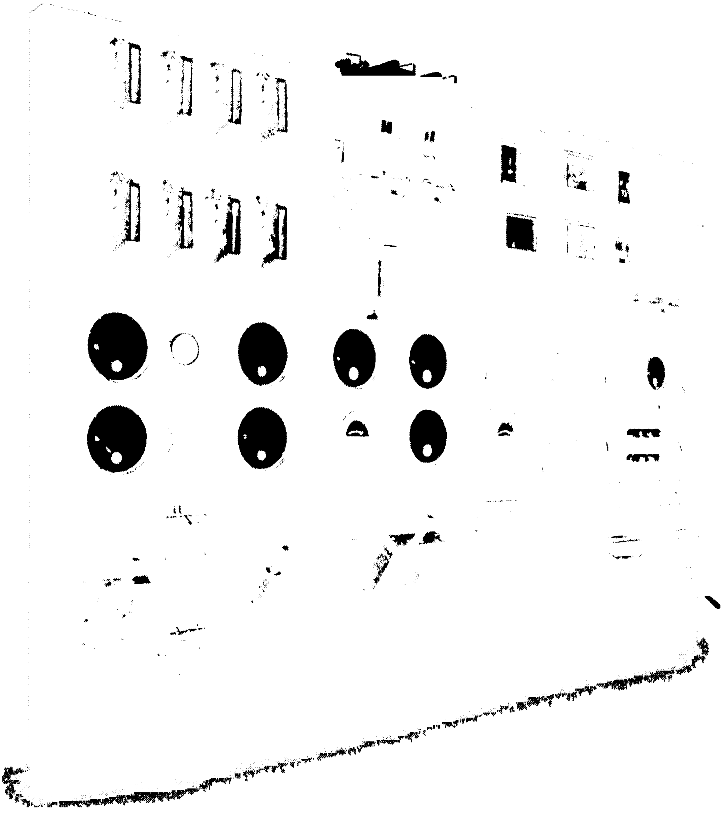


FIG. 221. MAIN SWITCH- AND CONTROL-BOARD

English Electric Co

Control Switchgear. The main control board, shown in Fig. 221, is of the standard slate-fronted flat-back type, and has mounted upon it the relays, contactors, and control switches necessary to the automatic control of the installation as a whole. It consists of four panels, the first of which (on the extreme right) carries the bulk of the equipment controlling the rectifier auxiliaries, the ignition and excitation supply, and the grid control apparatus.

The chief item on this panel is the automatic vacuum-indicating and control relay, its auxiliary relays, and the constant-current barreter. The movement of the relay is fed from the standard Pirani unit, the detector of which is situated in the vacuum. Above the moving pointer (which moves over a scale calibrated from 0–100 microns) is a chopper-bar which, actuated from an electrically-wound clockwork device, chops down at frequent intervals and causes the pointer and a fixed contact attached to it to move downwards. Underneath these are three adjustable contacts, each connected to an auxiliary relay. When the pointer is forced down by the chopper-bar it will close any one of the three contacts over which it may be located at the time, which in turn will cause the corresponding auxiliary relay to close.

The three contacts are so situated under the pointer that the right-hand one will close when the vacuum is high, the middle one when the vacuum is low (but not dangerously low) and the left-hand one when the vacuum is dangerously low (i.e. "soft"). Each of the three auxiliary relays will therefore close under one of the above conditions. The relay which closes when the vacuum is "soft" causes the equipment to be tripped and locked out of service. When the vacuum is slightly below the normal operating condition, the second relay causes the vacuum pumps and their associated auxiliary equipment to start up. When the vacuum is high the third relay shuts down the vacuum pumps.

When the rectifier is in service the two "high" and "low" contacts are made ineffective, as the pumps are then always kept running. The "soft" circuit always remains effective. The vacuum-indicating and control equipment, therefore, ensures that the rectifier vacuum is maintained in a sound condition, no matter whether the unit is running or not; or, if this becomes impossible, the equipment is cut out of action, thus preventing the rectifier from attempting to run under conditions of poor vacuum.

At the back of this control panel are mounted the numerous auxiliary items, among which may be mentioned the transformer, three-phase metal-oxide rectifier, and potentiometer supplying the grid bias.

The second panel comprises the equipment for initiating the starting-up and shutting down of the installation, and the voltage-regulating and load-limiting relays whose action is described later.

The third panel carries the main direct-current circuit-breaker, isolating switches and ammeters. The solenoid-operated double-pole circuit-breaker is of the automatically reclosing type, which, on tripping due to an overload or fault, recloses after a time interval which is adjustable. The reclosing gear is set to limit the possible reclosing impulses to a predetermined number after which the breaker remains open and the whole equipment is shut down. Should the breaker remain in for a given time after reclosing for a number of times less than the predetermined number, the counting gear will reset back to give the full number of possible reclosures should a further fault or overload occur.

The fourth panel is equipped with the necessary control gear for automatically starting and protecting the rotary balancer, and also carries ammeters, voltmeters, mid-wire switch and a double-throw double-pole switch by means of which the balancer can be connected either direct to the substation bus-bars or to the rectifier terminals. Normally the balancer is connected to the rectifier terminals.

Automatic Features. A comprehensive system of protection is incorporated in the automatic control, covering—

(*a*) Alternating-current overload.
(*b*) Direct-current overload.
(*c*) Failure of alternating-current supply.
(*d*) Soft vacuum.
(*e*) Excessive rectifier temperature.
(*f*) Loss of water pressure.
(*g*) Direct-current reverse current.
(*h*) Overload on the balancer.
(*i*) Balancer shuts down or fails to start, or is switched out by mistake.
(*j*) Failure of equipment to complete the starting sequence.
(*k*) Failure of the auxiliary supply.
(*l*) Locking-out of the direct-current breaker.

Conditions *a*, *b*, *e*, *f*, *g*, *h*, *i*, *j*, *l*, cause a "lock-out," i.e. the equipment shuts down and will not restart until a visit has been made to the substation. After the trouble has been corrected, the lockout-relay may be reset. Overload on the alternating-current side locks out the equipment because the inverse time relays are so set that ordinary overloads will be cleared by the direct-current breaker, and only a dangerous overload condition will operate the alternating-current overload relays.

Conditions *c* and *k* are external to the plant; and if they revert to normal again the equipment is enabled to restart. Condition *b* is covered by the auto-reclosing gear and lock-out attachment for *l*, and by the apparatus covering *a* and *c*, which will cause a lock-out if the direct-current overload persists.

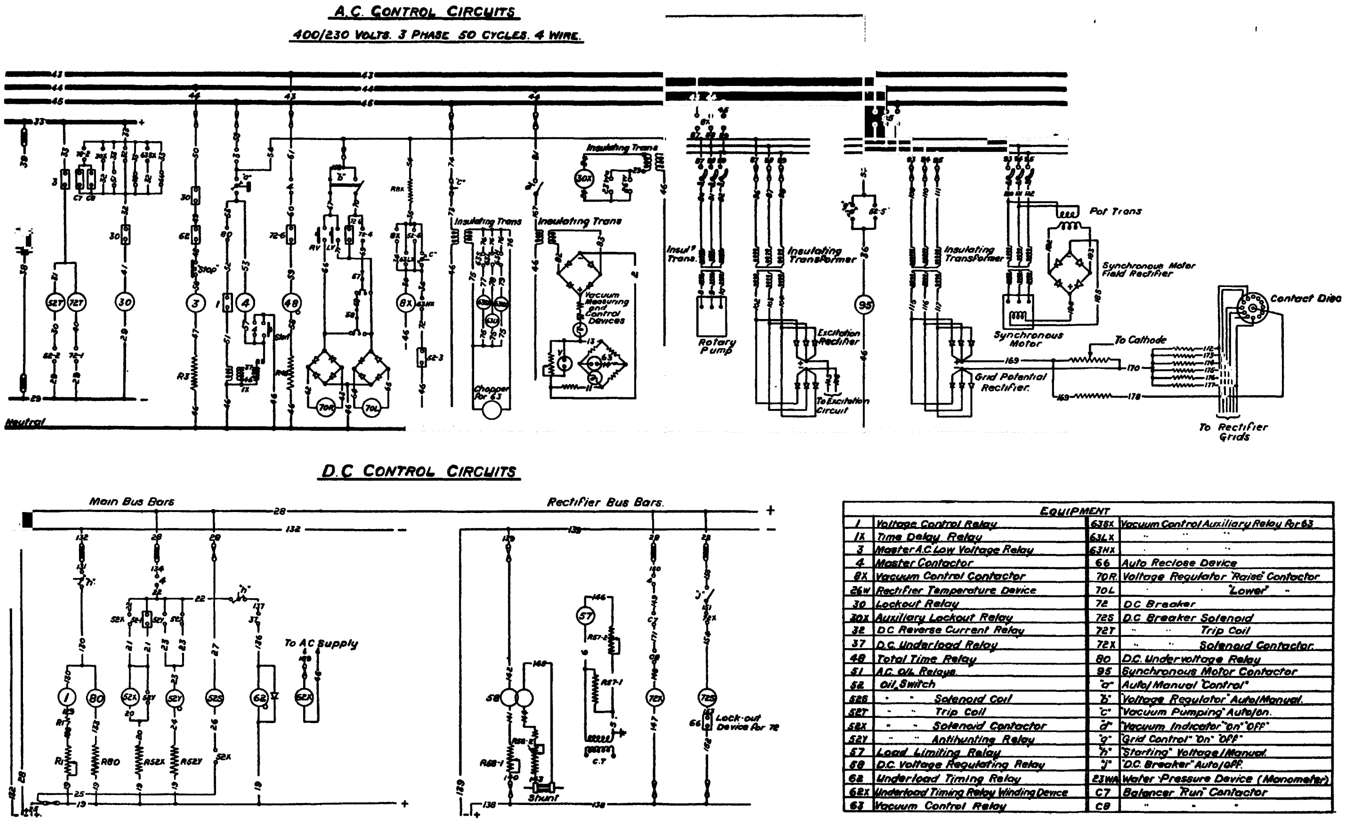
Starting-up. The following describes, step by step, the functioning of the equipment from starting to shut-down. Reference should be made to the schematic diagrams in Figs. 222 and 223.

Provided all the protective items are in the normal positions, and the alternating-current voltage is sufficiently high, then a start is possible. As soon as the output voltage falls to the predetermined low value corresponding to the setting of relay 1, and provided that it is not so abnormally low as to cause relay 80 to open its contacts, then time-delay relay 1*X* will be energized from its auxiliary transformer.

After the time interval of relay 1*X* has elapsed, the latter will cause master contactor 4 to close, which in turn will energize the oil-switch closing solenoid contactor 52*X* and the total time relay 48.

The oil-switch solenoid 52*S* will now be energized, also relay 52*Y*. The circuit-breaker will close and relay 52*Y* will cause the solenoid contactor 52*X* to be de-energized and make it impossible for it to be re-energized except after a restart, thus preventing the solenoid from "hunting" should the breaker fail to become properly latched in. The main transformer and hence the anodes are now alive, and as several auxiliary contacts 52–4, 52–5, etc., on the oil-switch have closed, contactors 8*X* and 95 have also closed, and all the auxiliary circuits are now energized from the auxiliary transformer.

The rotary vacuum pump starts up, the rectifier receives its excitation supply, the mercury vacuum pump heater starts to warm up, the grid-control synchronous motor runs up and comes into step with its field excited, and the grid bias metal rectifier is energized and excites the grids. The ignition anode



EQUIPMENT			
1	Voltage Control Relay	63SX	Vacuum Control Auxiliary Relay for 63
1X	Time Delay Relay	63LX	” ” ”
3	Master A.C. Low Voltage Relay	63HX	” ” ”
4	Master Contactor	66	Auto Reclose Device
8X	Vacuum Control Contactor	70R.	Voltage Regulator "Raise" Contactor
26W	Rectifier Temperature Device	70L	” ” "Lower" ”
30	Lockout Relay	72	DC Breaker
30X	Auxiliary Lockout Relay	72S	D.C Breaker Solenoid
32	DC Reverse Current Relay	72T	” ” Trip Coil
37	D.C. Underload Relay	72X	” ” Solenoid Contactor.
48	Total Time Relay	80	D.C. Undervoltage Relay
51	A.C. O/L Relays.	95	Synchronous Motor Contactor
52	Oil Switch	"a"	Auto/Manual "Control"
52S	” ” Solenoid Coil	"b"	"Voltage Regulator" Auto/Manual.
52T	” ” Trip Coil	"c"	"Vacuum Pumping" Auto/on.
52X	” ” Solenoid Contactor	"d"	"Vacuum Indicator" "on" "Off"
52Y	” ” Antihunting Relay	"g"	"Grid Control" "On" "Off"
57	Load Limiting Relay	"h"	"Starting" Voltage/Manual.
58	D.C. Voltage Regulating Relay	"j"	"D.C. Breaker" Auto/off.
62	Underload Timing Relay	23WA	Water Pressure Device (Manometer)
62X	Underload Timing Relay Winding Device	C7	Balancer "Run" Contactor
63	Vacuum Control Relay	C8	” ” ”

FIG. 223. KEY DIAGRAM OF ALTERNATING-CURRENT AND DIRECT-CURRENT CONTROL CIRCUITS
English Electric Co.

dips into the mercury, and as the excitation arc is struck there is a potential at the rectifier terminals.

Meanwhile the contact-disc rocking motor has moved the disc to the low-voltage limit position. The value of this voltage is set so that it will be somewhat lower than the bus-bar voltage, and hence there is no tendency for the rectifier to seize the load the moment the direct current breaker closes.

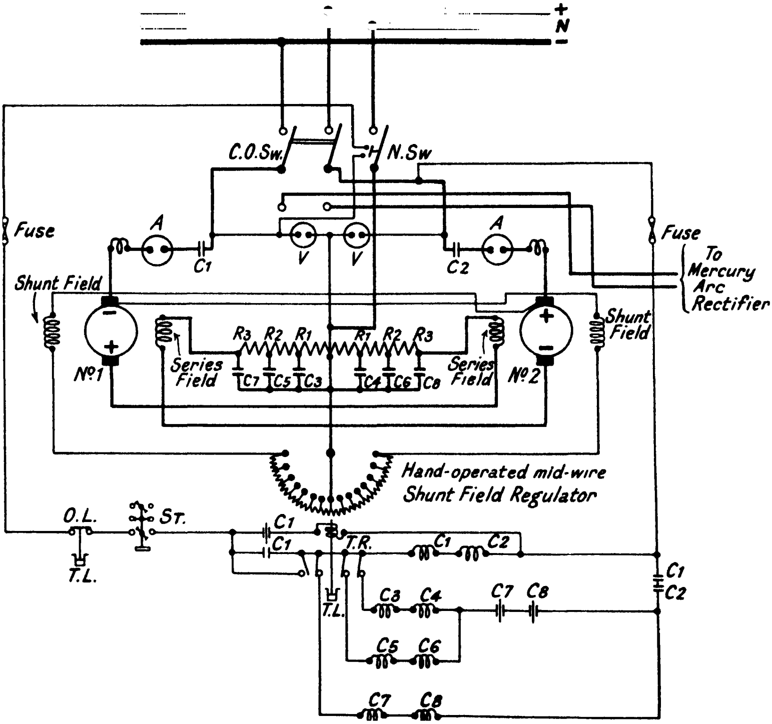


FIG. 222. DIAGRAM OF CONNECTIONS OF AUTOMATIC BALANCER SET
English Electric Co.

The balancer starting-time relay *T.R.* picks up when the rectifier is made alive on the direct-current side. As soon as relay *T.R.* picks up, it closes the balancer line contactors *C*1 and *C*2, which energize the balancer units through the starting resistance, de-energize *T.R.* and prepare circuits for the closing of contactors *C*3, *C*4, *C*5, *C*6, *C*7, and *C*8. The balancer now starts to rotate. Relay *T.R.* falls slowly against the resistance of an oil dash-pot and it closes, pair by pair, contactors *C*3 and *C*4, *C*5 and *C*6, and *C*7 and *C*8. In this way the starting resistance is cut out step by step, until finally the balancer is connected straight across the line and runs at full speed.

When the "running" contactors *C*7 and *C*8 close they cause the direct-current breaker solenoid contactor 72*X* to be energized, which in turn energizes the solenoid 72*S* and the breaker 72 closes. The solenoid is then de-energized by a device attached to the breaker.

As the direct-current breaker closes, one auxiliary switch opens releasing the voltage-regulating gear from the impulse which has caused the disc to rotate to the minimum-voltage position. Another auxiliary switch closes, putting the voltage under the control of the voltage-regulating relay 58 and the load limiting relay 57.

At the same time that the direct-current breaker 72 causes the voltage-regulating gear to come into action, it de-energizes the total time relay 48 to complete the starting sequence.

Voltage Regulation. Voltage-regulating relay 58 has two exciting coils, one energized from the direct-current bus-bars, and one connected in opposition to the former and energized from a shunt in the rectifier main connections. At no-load the first winding only is effective and allows the relay to balance only at the predetermined no-load voltage, the relay thus causing the contact disc to revolve until the no-load voltage is reached.

As the rectifier picks up load, the winding connected to the shunt becomes energized and "bucks" the first winding, upsetting the balance of the relay, and in turn causing the voltage to be raised further in order to restore the balance. Thus, as the load rises the voltage rises also, giving an over-compound characteristic to the rectifier.

Under certain conditions an over-compounded rectifier attempts to seize the available load. To prevent this, the load-limiting relay 57 is included. This relay has its exciting coil connected to a current transformer included in the main alternating-current circuit of the oil switch, and has its contacts so connected in the voltage-regulating circuits that should the load rise to the predetermined limiting value, it prevents the voltage-regulating relay 58 from raising the voltage any further. Should, however, the load still rise, due to some external cause, then the load-limiting relay will cause the contact disc to rotate so as to lower the voltage until sufficient load has been thrown off. When the severe load condition ceases the voltage-regulating relay takes over control.

The no-load value of voltage is adjustable by means of a rheostat, as is also the percentage of over-compounding and the value at which the load will be limited. The voltage at which the rectifier will start up, and the current at which it will shut down, as well as the two corresponding time lags, are adjustable.

Shutting Down. When the load falls to the pre-set value, relay 37 energizes the timing device 62, the time lag of which is adjustable up to half an hour and incorporates an electrically-wound clock. The time-interval relay 62 opens its contacts, thus in turn causing relay 3 to drop out. The opening of relay 3 causes both the oil switch and the direct-current breaker to trip and all auxiliary circuits to be de-energized; so that all items reset to the shut-down positions, after which 62 makes circuit and 3 picks up ready for a further start.

All necessary control switches and push buttons are provided, so that the equipment can be operated manually in cases of emergency or for testing purposes.

(5) GRID-CONTROLLED GLASS-BULB RECTIFIER EQUIPMENTS WITH A VARIABLE VOLTAGE-CHARACTERISTIC

The field of application of the mercury-arc rectifier has been greatly extended by the development of grid control, and improvement in the method of applying this control has placed the rectifier in a very favourable position in cases where special characteristics are required.

Before the application of control grids to the mercury-arc rectifier, the only methods available for compounding the voltage characteristic were by a tap-changing device on the main transformer, or by an induction regulator operating on the primary or secondary side of the rectifier transformer. In the former method the voltage variation must necessarily take place in steps. In the latter method the voltage variation is smooth between the required limits, the size or capacity of the controlling unit being proportional to the range of voltage covered by the particular characteristic. The development of the grid-controlled mercury-arc rectifier, on the other hand, has resulted in the production of a compounding conversion unit, which has perfectly smooth voltage control between any desired limits. It is unaffected in size for any voltage range, and is easily adaptable to automatic working. The energy loss in the controlling apparatus itself is small, and thus maintains the high-efficiency feature of the straight rectifier.

The facility with which a grid-controlled equipment can be adapted to give a direct-current supply requiring a heavily over-compounded voltage characteristic is exemplified in the glass-bulb rectifier installation supplied by the English Electric Co. to the order of the Wallasey Corporation. Previous to the conversion of the tramway system, an outlying pumping station in connection with the Corporation water supply was supplied from the traction station through a long feeder. The pumping station contains two motor-driven pumps, which are controlled by means of floats. Voltage conditions on the traction bus-bars precluded full compensation for the heavy feeder drop, and it was decided to install a conversion unit which would be sufficiently compounded to maintain normal voltage at the pumps, when the changeover took place.

Main Features. The installation consists of two rectifier cubicles each rated at 120 kW and supplied from separate transformers. In order to compensate for the feeder drop and maintain the rated voltage of the pump motors, it was necessary to compound the rectifier to give a no-load voltage of 500, and a full-load voltage of 600, with a mean value of about 550 volts at half load with only one pump in operation.

Although one of the rectifier units is maintained as a standby in view of the importance of the pump-motor load, it was specified that the voltage characteristic of both units should be adjustable between wide limits, to enable either rectifier to feed local circuits in parallel with rotary convertors when occasion demanded.

Each rectifier unit is supplied from a three/six-phase fork-connected transformer, the primary supply being at 50 cycles and 6 600 volts, whilst primary taps of ± 2½ per cent and ± 5 per cent are provided. The transformers are of the oil-immersed type, and incorporate special features in their design necessary for satisfactory operation when feeding rectifiers.

The rectifier cubicles follow the general lines of the English Electric Co.'s construction for this class of apparatus, and are illustrated in Figs. 224 and 225. The cubicles are arranged for front access, with a voltmeter, ammeter, equalizer switch, and hand-wheel for adjustment of compounding, mounted on the

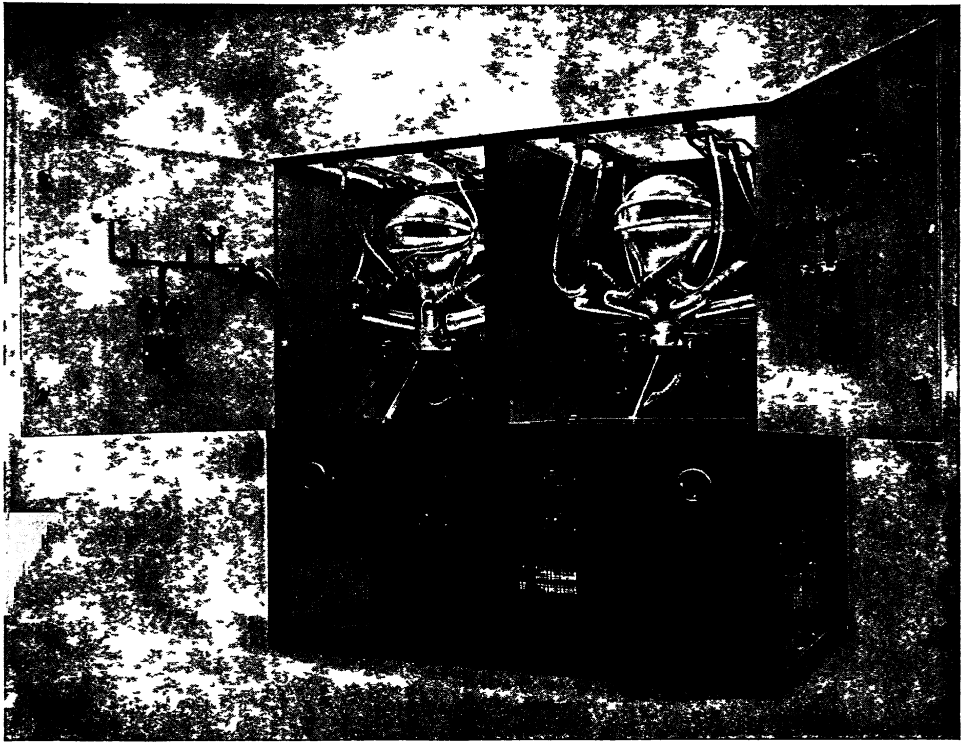


FIG. 224. TWO 120 KW GRID-CONTROLLED GLASS BULB RECTIFIER UNITS

English Electric Co

front panel. Each rectifier cubicle contains a six-anode rectifier bulb fitted with control grids, which is rated at 200 A continuously and capable of liberal overloads. Stability of the main arc down to no-load is maintained by two excitation anodes fitted near the cathode chamber. Ignition is effected by a spring-pivoted electrode which normally dips into the cathode mercury. When the alternating-current supply is switched on, the electrode is raised by the action of a solenoid, producing a small arc which commences ionization and allows the excitation arc to strike. The ignition circuit is controlled by a relay which opens the circuit when the excitation arc is established.

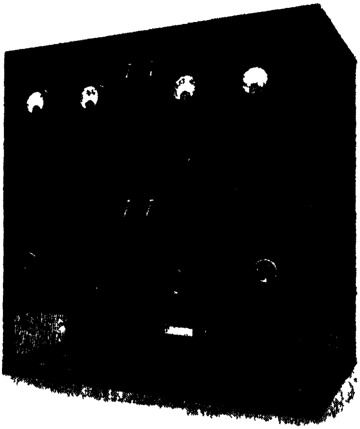


FIG. 225. FRONT VIEW OF CUBICLES CONTAINING 200-A RECTIFIERS
English Electric Co

Cooling of the rectifier bulb is provided by a multi-blade fan which is entirely silent in operation. Heavy-duty fuses are incorporated for protection of the anodes. Over-voltage protection is provided by surge-absorbing resistances having a special characteristic. A cathode choke of liberal proportions is connected in the positive lead to ensure a smooth direct-current supply to the motors.

The type of grid-control system used in this equipment is

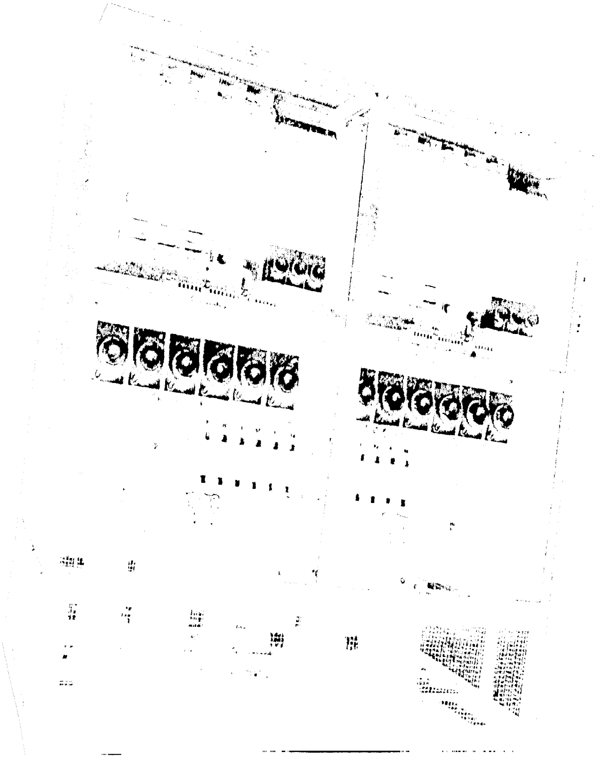


FIG. 226. REAR VIEW OF CUBICLES SHOWING ANODE FUSES AND GRID-CONTROL PANEL
English Electric Co.

the saturated transformer method, the advantages of which, such as its "hard" control, instantaneous response to varying loads, and completely static operation have already been described in an earlier chapter (IX). The complete control unit is mounted on a panel and forms a compact arrangement in the upper portion of the rear compartment of the cubicle, as will be seen from Fig. 226. The grid-control panel is shown separately in Fig. 228.

Grid-control System. The principles underlying the operation of the control unit may be best described by referring to the diagram of connections shown in Fig. 227. Small highly-saturated transformers are used for providing the impulses to the grids of the rectifier, the instant of ignition being controlled by saturating chokes in which the controlling influence is a function of the direct-current load.

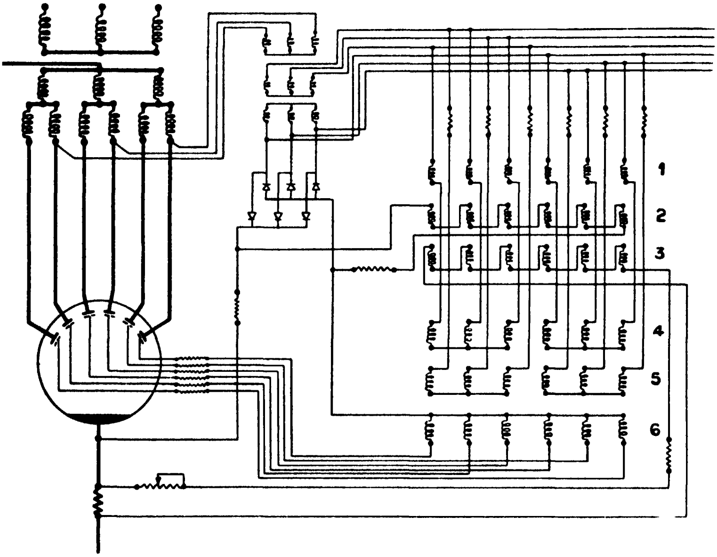


FIG. 227. DIAGRAM OF CONNECTIONS OF GRID-CONTROL UNIT
English Electric Co.

The windings of the saturated chokes are marked 1, 2 and 3, and there are six groups, one per phase. The cores are omitted from the diagram for simplicity. Each of the impulse transformers forming the lower groups has an impulse winding 6 connected to the grids of the rectifier, and two excitation windings 4 and 5, the cores being constructed of high permeability material. A small metal-oxide rectifier provides the negative bias on the grids, and, in addition, supplies the exciting current to the pre-magnetizing windings of the chokes.

It will be seen from the diagram that the exciting currents

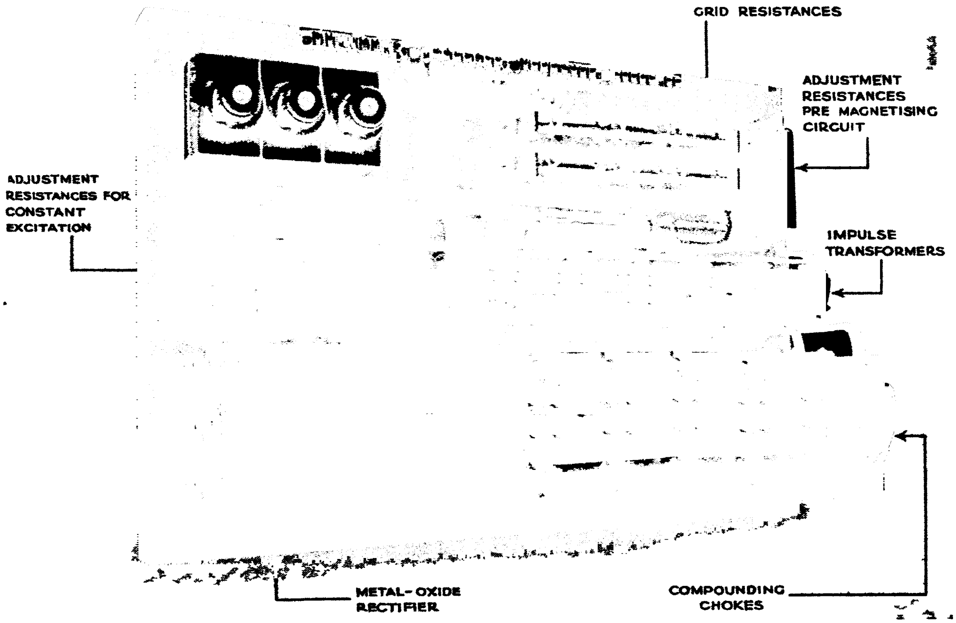

GRID RESISTANCES
ADJUSTMENT RESISTANCES PRE MAGNETISING CIRCUIT
ADJUSTMENT RESISTANCES FOR CONSTANT EXCITATION
IMPULSE TRANSFORMERS
METAL-OXIDE RECTIFIER
COMPOUNDING CHOKES

FIG 228. GRID CONTROL PANEL
English Electric Co

of the impulse transformers have a definite phase displacement, and, further, one is maintained constant in value, while the other is varied by the impedance of the choke winding. This feature is shown in the upper diagram of Fig. 229, the constant excitation as I_c and the variable excitation as I_v. The resultant excitation will, therefore, be periodic, and the instant of reversal will depend on the relative value of the variable component. In consequence of the high permeability of the core, the flux wave is flat-topped, and at the instant of its rapid reversal will induce a voltage impulse in the grid winding 6. It is possible to limit the duration of the impulse to about 10 degrees by correctly proportioning the various factors in the design, and thus produce an ideal form of "hard" control. The value of the voltage impulse is such that it exceeds the negative bias of the grid relative to the cathode, and at that instant enables the corresponding anode to ignite.

Voltage Control. Variation in the value of I_v is produced by the action of the saturating choke, the core of which is premagnetized from the metal-oxide rectifier as mentioned before. This pre-magnetization is neutralized by the ampere-turns of winding 3, which is excited from a shunt in the main positive circuit of the rectifier. The saturation of the core of the choke is, therefore, approximately inversely proportional to the load on the rectifier and the variable impedance of winding 1 produces the necessary variation in the value of excitation of the impulse transformer. When the load increases the variable excitation is weakened, and when the load decreases the variable excitation is strengthened. Reference to the upper diagram of Fig. 229 will show that the effect of this is to move the instant of reversal—or generation of impulse—to the left or right respectively, producing a higher or lower output voltage.

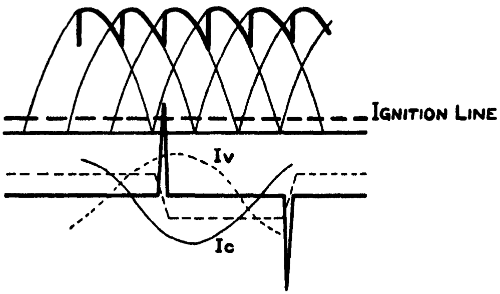
In the lower half of Fig. 229 the quantities are shown vectorially, and the relative values with the effect on the ignition angle can be readily seen.

In this diagram—

OA and *OA'* represent the anode voltage vector at full-load and no-load respectively.

A'OA is the angle of ignition advance between no-load and full-load.

OV, *OC* are the variable and constant excitation vectors corresponding to the full-load position.



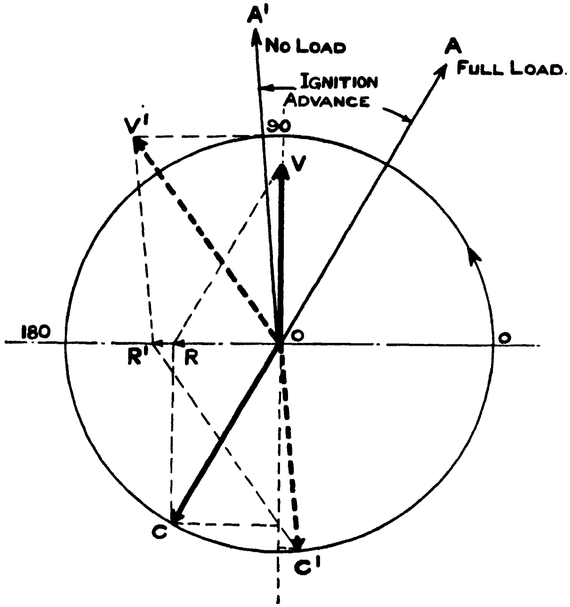


Fig. 229. Vector Diagram of Grid-control System

English Electric Co.

OV' OC' are similar quantities corresponding to the no-load position.

OR is the resultant excitation at full-load.

OR' is the resultant excitation at no-load.

The vectors *OV* and *OC* are linked by a constant angle determined by the selected phase displacement between the excitation of windings 4 and 5 of the impulse transformers. It will be seen that the value of the variable excitation must be such that at any instant the projection on the vertical axis must be equal and opposite to the projection of the constant excitation *OC*. Further, it will be observed that the resultant excitation has a value varying between *OR* and *OR'*, and that at the instant of ignition the value is zero, at which point the reversal of flux generates the voltage impulse in the grid coils 6. Having determined the amount of ignition advance necessary to give the required increase in voltage for compounding, the diagram will provide the relative values of the constant and variable excitation corresponding to this condition.*

A noteworthy feature of this control scheme is the fact that the amount of compounding is under complete control by varying the resistance of the de-magnetizing circuit fed from the shunt in the main circuit. The hand-wheel seen on the front of the cubicles controls a rheostat which varies the resistance in this circuit, so that the compounding is capable of being quickly adjusted to suit the conditions for which this equipment was supplied. In this type of control it is also possible to provide adjustment by which the desired characteristic can be raised or lowered as a whole, which is equivalent to changing the ratio of the main transformer.

Fig. 230 shows the actual characteristics obtained with these equipments. It will be noted that the compounding is perfectly smooth and has no pronounced "hump," and is, in fact, equal to that obtained on modern rotating converting plant.

The system of voltage regulation used in these equipments is ideal for rectifiers supplying traction or other rapidly-varying loads. The voltage response is instantaneous, as there are no relays, contactors or other moving parts which, by their inertia, inevitably introduce a time lag in the compounding. In addition, it is claimed that the system is also partially self-compensating for variation in the alternating-current supply voltage; and that in cases where these variations are of considerable amplitude the scheme lends itself readily to a simple modification which will maintain a steady output voltage in spite of wide fluctuations in the alternating-current system.

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* The author is indebted to Mr. W. R. Evans for the development of this ingenious vector diagram.

(6) A Steel-tank Rectifier Substation for Municipal Lighting and Power Supply, and Arranged for Either Fully-automatic or Remote Supervisory Control

The Ilford Borough Electricity Department has been supplying current to consumers since 1901, and to-day six convertor substations, twenty-five transformer substations, and about 400 miles of distribution cable are in service. The latest addition to the resources of the undertaking is the mercury-arc rectifier equipment at the Town Hall substation, which was laid down to relieve the growing load on the direct-current mains in the borough and to do away with the necessity of installing more cables; at the same time voltage regulation in the district has been materially improved. The station is completely equipped with plant and apparatus supplied by the General Electric Co. Ltd., and it will eventually house two 1 500-kW steel-tank mercury-arc rectifiers, each with its transformer, one 150-kW rotary balancer and all necessary switch and control gear. At present only one of the rectifiers is installed. The plant converts three-phase 50-cycle alternating current at 6 600 volts to direct current at 470–500 volts. The direct-current network is a three-wire system, and since the rectifier is essentially a two-wire convertor any out-of-balance current has to be taken care of by the rotary balancer.

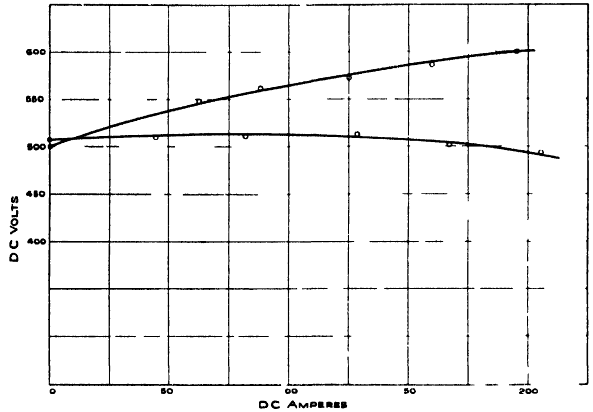

FIG. 230. VOLTAGE CHARACTERISTICS FOR LEVEL- AND OVER-COMPOUNDING

English Electric Co.

The substation is a brick building 40 ft. 6 in. by 32 ft. 6 in. A gallery runs along one side on which is installed the main high-tension switchgear, high-speed circuit-breakers, and smoothing choke coils. Below the gallery the control boards and direct-current feeder panels run nearly the whole length of the substation, the rectifier, main transformer, and balancer being installed on the other side of the building (Fig. 231). The main 6 600-volt switchgear consists of a four-panel truck cubicle switchboard with duplicate bus-bars. Two of the feeder units tap into a ring main and the third is an outgoing feeder. The fourth truck is fitted with a solenoid-operated oil circuit-breaker and controls the rectifier. Space is available for a further truck cubicle to control the second rectifier when it is installed.

Rectifier Unit. A view of the rectifier is shown in Fig. 232. Perhaps the most interesting feature embodied in the rectifier design is the patented seal, which consists of top and bottom members with iron cones between them, separated by a special vitreous enamel having a coefficient of expansion similar to that of iron. This construction possesses great mechanical strength and will stand a pressure test in excess of 20 000 volts, and the seal cannot be damaged by overheating. Because of the use of this seal, it has been found possible to dispense with water-cooled anode radiators, even though the rectifier has to carry 3 750 A for two hours. All "breakable" joints are of a metal-to-metal type, which has proved highly satisfactory in service. The rectifier tanks are made of heavy-section steel plate, so as to resist corrosion and to ensure long life.

The top plate, to which is welded the mercury vapour-condensing cylinder, carries the main and auxiliary anodes, whilst situated at the top of the condensing chamber are the solenoid-operated ignition anode and the two main valves, which serve to isolate the rectifier from the pump gear. At the bottom of the main cylinder is the insulated cathode mercury bath, which forms the positive pole of the outgoing supply. If it should be required for any reason to open up the rectifier for inspection, all that need be done is to remove the top-plate bolts, and the whole plate with diffusion pump can be lifted as a unit. Every part of the rectifier is easily accessible.

The patented anode grid is very effective, and it is claimed that the rectifier is capable of withstanding up to 33 per cent

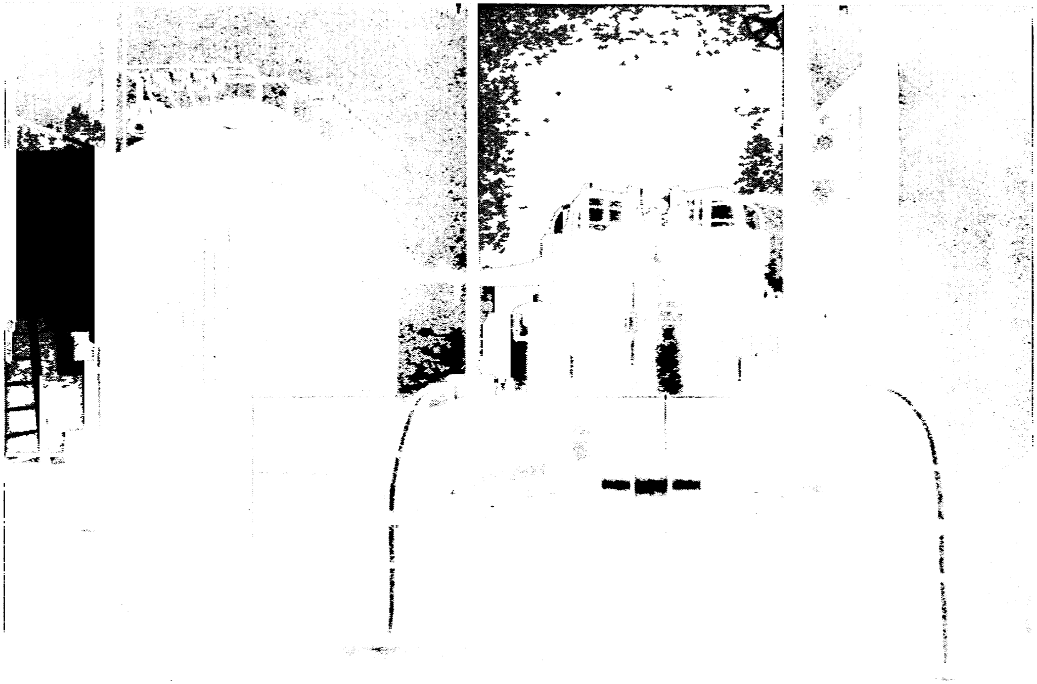

FIG. 231 1 500-KW STEEL-TANK RECTIFIER UNIT WITH 150-KW BALANCER SET
General Electric Co

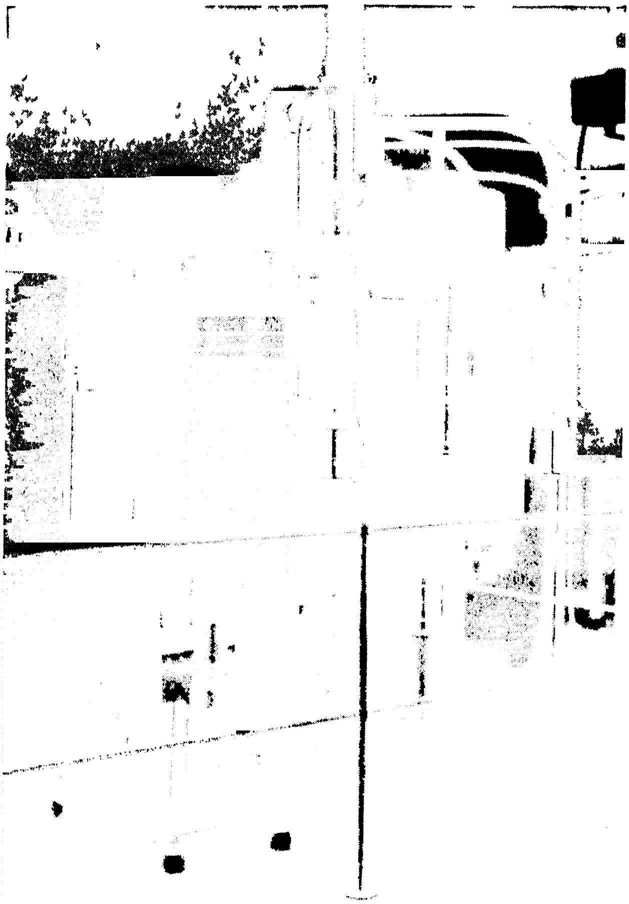

FIG. 232. 3 000 A STEEL-TANK MERCURY-ARC RECTIFIER
General Electric Co

overload momentarily, starting with the rectifier at a temperature of 10° C. The anodes are connected by cable to the secondary winding of the main transformer, which is connected in double three-phase with an interphase reactor, the neutral point of which forms the negative pole of the outgoing supply.

The rectifier transformer (seen in Fig. 231) is of the oil-immersed self-cooled type, the tap-changing gear and interphase reactor being mounted with the transformer in one tank.

Remote-control Equipment. The equipment is designed for operation by remote supervisory control from the Ley Street power station or alternatively for full automatic control. In the former case, the operation of small control keys on the remote control panel at Ley Street sends signals to the substation, which operates relays to start up or shut down the rectifier. In the latter case the plant is started up by a voltage relay operated from the direct-current side and shut down by an underload relay. Means are provided on the Ley Street control board to suspend the automatic operation if such a procedure should be required. The plant may also be operated by push-button control from the substation when necessary for testing or other purposes.

A single three-way controller on the control panel in the substation (Fig. 235) sets all apparatus for any one of the three methods of control mentioned above.

The supervisory control system is selective, employing five pilot wires to carry out all the operations required. There is no risk of mis-operation, as each selection is checked back before any operation is performed. Moreover, the same five pilot wires can be extended to practically any number of stations, and either similar or entirely different operations can be carried out from the one common sending equipment. As installed at Ilford it gives the following control facilities—

(*a*) Starts up rectifier.
(*b*) Shuts down rectifier.
(*c*) Indicates position of the rectifier oil circuit-breaker.
(*d*) Indicates position of the direct-current circuit-breakers.
(*e*) Raises output voltage by operating on-load tap-changing gear on main transformer.
(*f*) Lowers output voltage.
(*g*) Reads bus-bar voltage.
(*h*) Reads load current.
(*j*) Closes a contactor on the B.O.T. earthing panel, so that the system midwire may be earthed.
(*k*) Opens the above contactor.
(*l*) Indicates position of earthing contactor.
(*m*) Closes a contactor on the B.O.T. panel for short circuiting the earthing resistance.

(*n*) Indicates the position of the short-circuiting contactor.

(*p*) Gives an alarm if any automatic operation should take place on the direct-current circuit-breakers or high-tension oil circuit-breaker.

From the above it will be noticed that there are more than ten points concerned in the control. Two receiving cabinets are therefore employed at the substation, with the one set of five pilot wires looped into each. Thus for control purposes the apparatus is treated as if it were in two stations. A view of an operating cabinet is shown in Fig. 233.

The equipment at the control station consists of a group of keys, strips of lamps for indicating purposes, and meters, all of which are mounted on the front of a cabinet containing the associated selectors and relays. A view of the cabinet is shown in Fig. 234.

Apart from the economy effected, the principal features of the system are its simplicity and reliability. As an example, to carry out the operation necessary to put the rectifier into operation, the start key is first depressed, then a key is depressed corresponding to the number of the selected station, whereupon the selector apparatus at that station responds and is prepared to·receive further signals, all other stations being locked off the pilots for the time being. A check-back signal is transmitted to the control point to indicate which station has been selected. A further key is then operated, marked "Start Rectifier," whereupon the control apparatus at the particular substation selected is set in a position corresponding to the desired operation. Again, a check-back signal is received indicating correct preparation. Finally, the "operate key" is depressed to complete the operation and start the rectifier. When this operation has been carried out, a further signal is received showing that the rectifier oil switch has been closed. Other operations are carried out in a similar manner.

It will be seen that the provision of check-back signals for each individual function performed is a complete safeguard against incorrect operation.

Auxiliaries. As the plant is never called upon to start up when the direct-current bus-bars are dead, the supply for closing the oil circuit-breaker, and operating various auxiliary devices is drawn from the direct-current system. A small transformer, energized from the low-tension side of the main

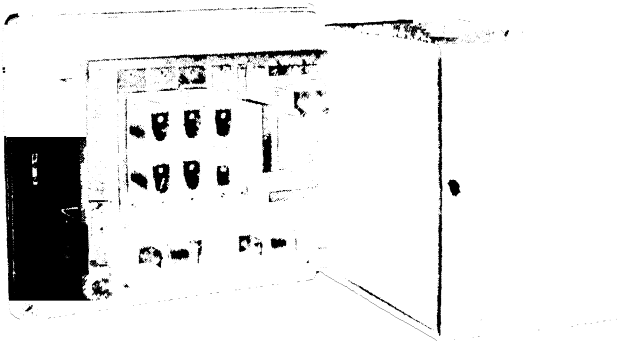

FIG 233 OPERATING APPARATUS CABINET FOR OPERATION FROM CONTROL CABINET SHOWN IN FIG 234

General Electric Co

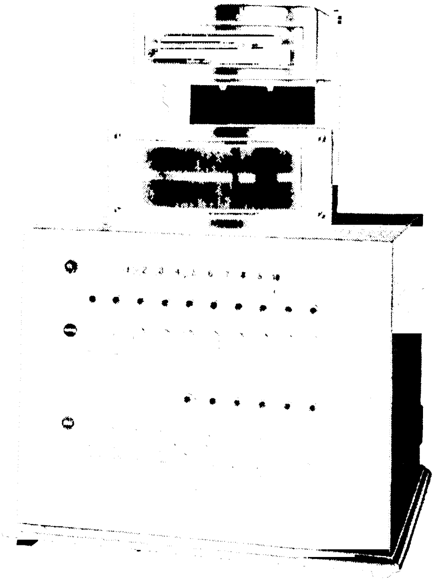

FIG 234. SUPERVISORY CONTROL CABINET FOR CONTROLLING RECTIFIER EQUIPMENT AND B O.T PANEL

General Electric Co

transformer, supplies current for the auxiliary anode circuit and power to the diffusion pump heaters.

The rectifier main tank and also the diffusion pump condensing chamber are both cooled by water from the town supply. If this supply should fail, a three-way valve operates to draw water from an emergency tank. Upon the resumption of the public water service the valve automatically operates to restore the normal supply. The diffusion pump water supply is controlled by hand-operated valves, since a constant

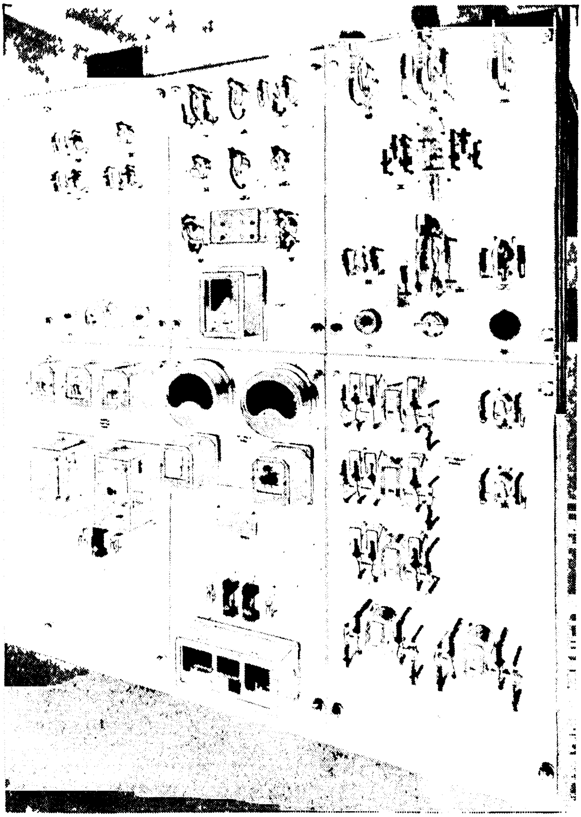

FIG. 235. AUTOMATIC CONTROL SWITCHBOARD FOR RECTIFIER EQUIPMENT
General Electric Co

small supply of water is required. The main cooling water supply is controlled by two valves. The first, an electrically-operated valve, operates to cut off the water completely when the rectifier is shut down. The second controls the flow of water through the rectifier when in service so as to maintain a nearly constant rectifier temperature. This valve is operated by a thermostat inserted in the rectifier tank.

The high degree of vacuum necessary within the rectifier is maintained by two pumps working in tandem. The pump maintaining the high vacuum is called the *diffusion pump*, and operates by boiling mercury and passing the vapour so formed through nozzles. In passing through these nozzles, gases in the rectifier chamber are picked up in the vapour stream. The mercury vapour is then condensed and passed back into the boiling chamber, and the gases pass into the interstage reservoir. The diffusion pump is kept in operation continuously, so that the rectifier is always ready for immediate service. The interstage reservoir is evacuated at intervals by a rotary box pump driven by a direct-current motor. This motor is started and stopped as and when required by a contact-making manometer gauge.

Control Features. The output voltage is maintained at the required value by on-load tap-changing equipment on the high-tension side of the main transformer. This gear is motor driven and controlled by a compound voltage-regulating relay. If desired, the tap-changing equipment can be operated by the supervisory gear from Ley Street or alternatively by push-buttons on the substation control board.

The starting sequence for the equipment is as follows.

(1) The starting impulse is received either from the supervisory gear, the low-voltage starting relay or the local push-button.

(2) The oil switch closes, energizing the main transformer and also the auxiliary anode circuit.

(3) The water is turned on to the main cooling system.

(4) After a flow of water has been established as indicated by the water flow relay, the ignition motor-generator set is started up and an arc struck between the ignition anode and the cathode. This arc quickly spreads to the auxiliary and main anodes which are already alive.

(5) The ignition motor generator set is shut down.

(6) Directly the oil circuit-breaker closes, the balancer-starting equipment becomes energized and the balancer set automatically runs up to speed.

(7) The balancer mid-wire contactor now closes and the balancer becomes loaded in the normal way.

(8) An interlock on the balancer mid-wire contactor closes the rectifier breakers and connects the rectifier to the bus-bars.

(9) The rectifier is normally paralleled with minimum output volts and consequently in general picks up no-load at first. However, the voltage-regulating relay now comes into operation and will function to increase the bus-bar voltage to the normal value. As the voltage rises, so the rectifier will become loaded.

(10) When the load rises above approximately 100 A, the main load relay operates to cut out the loading resistance, which is at first in circuit to reduce the 15 per cent voltage rise which occurs at very light loads. Should the load fall, this resistance is again put in circuit.

The rectifier may be shut down by one of the following methods—

(*a*) By the operation of the underload relay (when on automatic control).

(*b*) By the supervisory gear (when on remote control).

(*c*) By push-button in the substation (when on local control).

(*d*) At any time by the operation of a protective device.

In all cases the stopping impulse simply trips the oil circuit-breaker, when the balancer is shut down, the cooling water is shut off and all apparatus reset ready for the next start.

Protective Features. The equipment is protected against all faults which may occur on the rectifier and its control gear, and from damage which may occur from faults on the system to which the rectifier is connected.

The types of protection fall into two classes—

(1) Faults which shut the rectifier down, or prevent it from being started until conditions are again safe for running. With this type of fault the protective device resets itself automatically.

(2) Faults which shut the rectifier down and "lock out" the set. In these cases the station must be visited and the lock-out relay reset by hand before further running is possible.

In the first class are—

(*a*) *Protection Against Overheating of the Rectifier Top Plate.* If due to continued heavy loads the rectifier becomes overheated, it is shut down, but the cooling system continues to operate until the rectifier has cooled down to a safe temperature, when the unit automatically becomes ready for service again.

(*b*) *Failure of Cooling Water.* If there is a failure of the water supply for either the main or diffusion pump cooling systems, the water flow relays operate to shut down the unit and to prevent starting until the water service becomes available again.

(*c*) *Failure of Vacuum.* If the vacuum in the rectifier becomes poor, the rectifier is shut down and held out of service until a good vacuum is restored.

In the second class of protections are—

(*d*) *Excessive Overload on the Balancer.* If the balancer breakers trip due to excessive overload, the lock-out relay is operated and the plant shut down until the lock-out relay has been reset.

(*e*) *Overload or Earth Leakage on the Main Transformer,* and

(*f*) *Direct-current Overload.* The lock-out relay is operated as before.

(*g*) *Faulty Start.* At the beginning of the starting sequence a time delay relay is started which is stopped again when the sequence is completed. Normally this relay is not energized long enough to close its contacts, but should the sequence be stopped for any reason the relay will run on to close its contacts and operate the lock-out relay.

Finally the oil circuit-breaker is provided with a no-volt coil, so that should there be a failure of the operating supply the plant will be shut down rather than be left running uncontrolled.

A simplified diagram of the main connections of the rectifier equipment is given in Fig. 236.

(7) A GLASS-BULB RECTIFIER UNIT FOR MUNICIPAL TRACTION SUPPLY, AND ARRANGED TO DEAL WITH REGENERATED POWER

The manifold advantages associated with the use of mercury-arc rectifiers for electric railway supply are not less prominent where municipal electric traction is concerned; and whilst the tramway systems in the great majority of our cities and larger

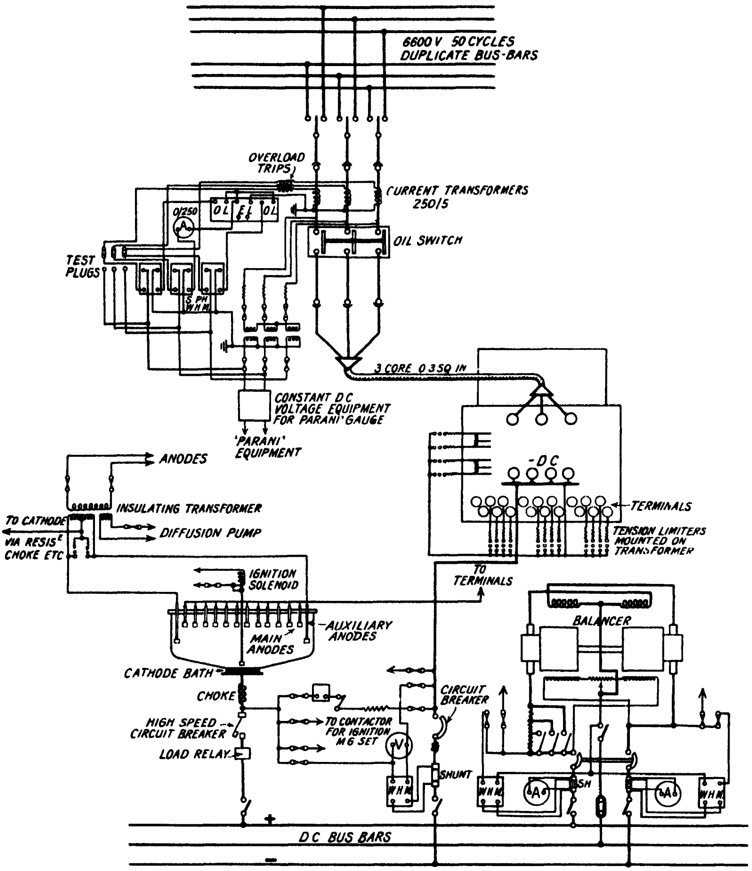

FIG. 236. SIMPLIFIED DIAGRAM OF CONNECTIONS OF RECTIFIER SUBSTATION

General Electric Co.

towns are irrevocably becoming obsolete—if not anachronistic—many civic authorities favour the electric trolley-bus as a more economic means of meeting the ever-increasing demands of municipal transport than that presented by the alternative petrol or heavy oil engined vehicle.

In most cases where tramway transport has been superseded in this way, a system of regenerative braking is employed in the trolley-buses; and it is therefore necessary that the traction substations should at times be capable either of returning the regenerated surplus to the alternating-current supply system, or of dissipating this energy in as convenient a manner as possible. The former solution* is justifiable commercially only if the aggregate amount of energy regenerated is large compared with the total energy output of the convertor substation. Such cases are naturally of very rare occurrence in municipal traction supply and, as a rule, arise only in the supply of electric railways in regions where long and steep grades have to be negotiated. In the case of trolley-bus traction, where only a small fraction of the regenerated energy ever appears as a surplus to be dealt with by the rectifier substation, it is the usual practice for a ballast resistance to be switched momentarily into circuit, across the substation busbars, to absorb and dissipate the energy carried by the surplus current available from the traction system.

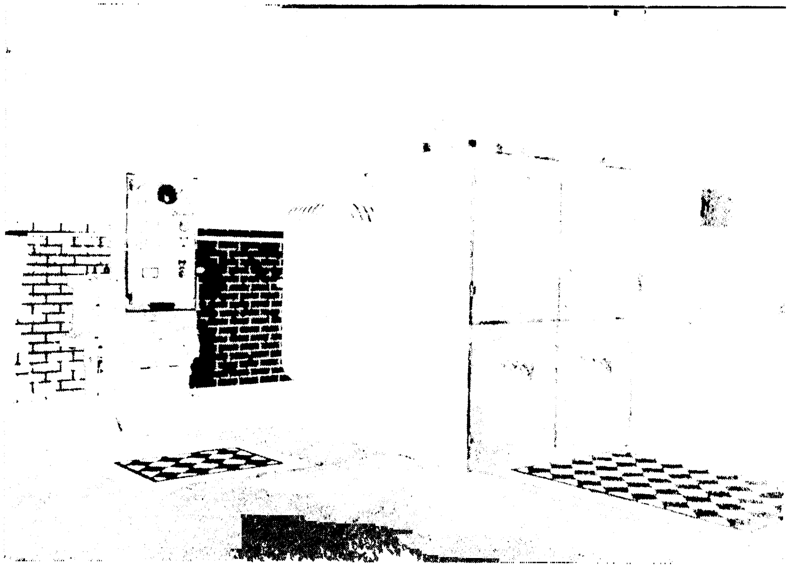

FIG 237 300-kW GLASS-BULB RECTIFIER EQUIPMENT IN FARNWORTH POWER HOUSE

Bruce Peebles & Co

An example of this method of control is afforded by the 300-kW glass-bulb rectifier equipment installed in the power house of the Farnworth Urban District Council. The traction load comprises both tramcars and trolley-buses, and the system operates at 600 volts (at the substation bus-bars). The converting equipment, which was supplied by Messrs, Bruce-Peebles & Co., consists of a double-cubicle glass-bulb rectifier unit (Fig. 237) which is connected to the 10 000-volt three-phase 50-cycle supply *via* a motor-operated circuit-breaker controlled by a time switch.

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* *Cf.* Chapter XI.

In Fig. 238, showing a front view of the two rectifier cubicles with both top and bottom doors open, the method of mounting the bulb with its base completely enveloped by the fan shroud is clearly seen. The anode fuses are accommodated in the lower compartment of each cubicle; whilst the horn-gap surge arrestors, connected across the phases of the secondary winding of the rectifier transformer, are mounted along the top of the cubicles. The transformer itself is placed immediately behind the latter, as shown in Fig. 237.

The method of arc ignition employed is interesting in that the more usual solenoid-operated ignition anode gives way in the Bruce-Peebles rectifier to a tungsten electrode fitted with bi-metal strips formed of two thicknesses of metal having different coefficients of expansion, and in consequence being susceptible to deflection under the influence of heat, such as that generated by the passage of a current through the electrode. The latter, which is controlled by an ignition relay, normally dips into the mercury and strikes an arc by breaking contact with the cathode surface almost immediately after the current is switched on. The excitation anodes then come into operation in the usual way, followed by the main anodes as soon as load is available.

The ballast resistance, whose function it is to dissipate the surplus regenerated energy which at times finds its way to the substation, is brought into circuit by means of a voltage relay which comes into operation whenever the direct-current bus-bar voltage exceeds a certain predetermined value. As soon as regeneration ceases—as determined by a return to normal value of the bus-bar voltage—the voltage relay operates so as to cut the ballast resistance out of circuit. The relay panel for controlling the ballast resistance may be seen to the left of the rectifier equipment in Fig. 237.

A simplified diagram of connections of the complete rectifier installation is given in Fig. 239.

(8) A REMOTE-CONTROLLED STEEL-TANK RECTIFIER SUBSTATION INSTALLED IN A RESIDENTIAL AREA

One of the outstanding features—in fact the most outstanding—of the mercury-arc rectifier is its almost complete silence in operation. It is the entire absence of the penetrating and persistent noise associated with high-speed rotating converting plant which makes the rectifier specially suitable for installation in residential districts, or in buildings where silence is desirable.

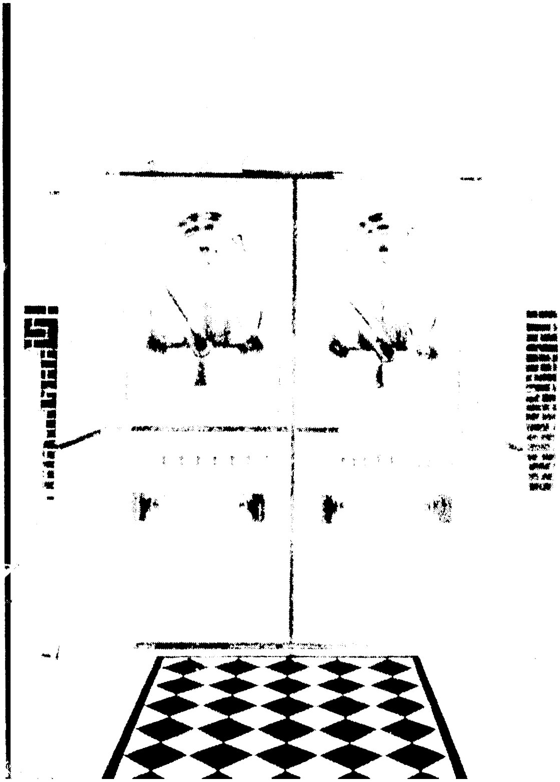

FIG. 238. FRONT VIEW OF RECTIFIER CUBICLE SHOWN IN FIG. 237

Bruce-Peebles & Co.

An interesting example of a substation where this factor was instrumental in determining the choice of the converting plant is furnished by the College Road Substation of the Harrow Electric Light and Power Co. The substation is arranged for remote control, and is equipped with a 1 000-kW Bruce-Peebles rectifier unit of the steel-tank type (Fig. 240).

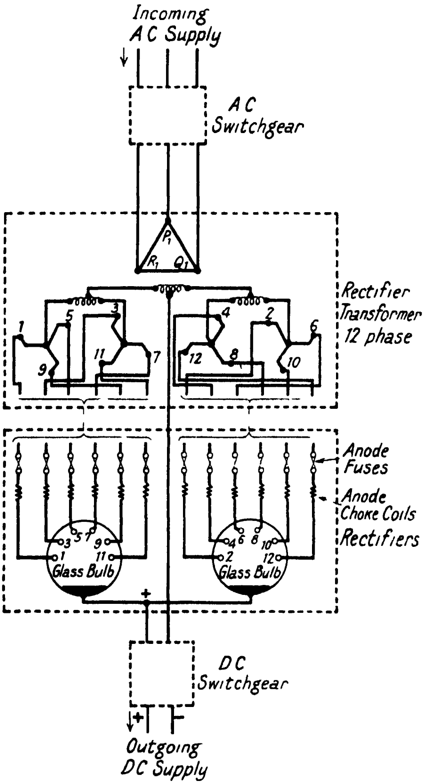

FIG. 239. SIMPLIFIED DIAGRAM OF CONNECTIONS FOR EQUIPMENT OF FIG. 237

Bruce-Peebles & Co.

Substation Buildings. The building is a simple brick structure, and ample space has been allowed for additional units to meet future requirements. Elevation and plan views in Figs. 241 and 242 show the arrangement of substation equipment. Transformer cubicles form one side of the building and are separated from the substation proper by a brick partition, access being from outside only. One side of the interior is occupied by the rectifier equipment and recoolers, while the switchgear is located at the opposite side. The relatively small weight of the rectifier dispenses with the necessity for special foundations, or reinforcing. To facilitate handling, a girder is provided in the most convenient part of the building, while a transport carriage enables the rectifier to be moved as required. The substation is ventilated by louvres fitted at the bottom of the main entrance doors, and the air, before passing to the outside of the building, is expelled over the top of the transformer cubicles by an outlet duct from the recooler, this arrangement creating a circulation of air which assists in the cooling of the transformers

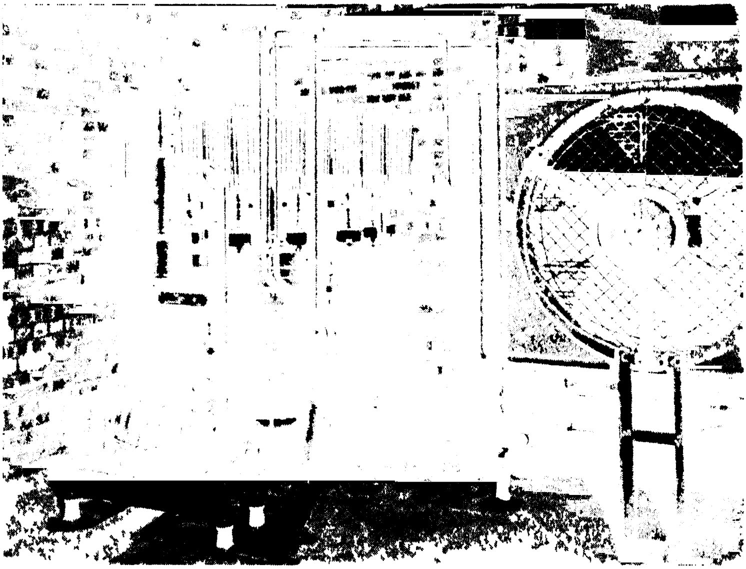

Fig. 240. 2 000-A. Steel-tank Rectifier Unit

Bruce-Peebles & Co.

Rectifier and Equipment. The rectifier is of the steel-tank type, constructed with twelve anodes, with a normal rating of 2 100 A at 450–500 V direct current. It is designed to withstand overloads of 25 per cent for two hours, and 100 per cent for 15 sec. The general appearance of the rectifier is shown in Fig. 240. In this case the preliminary vacuum pump, driven by a small low-speed alternating-current motor, is separately mounted upon an insulated base, but it is of interest to note that this auxiliary could be mounted without difficulty direct on the rectifier tank, thus making a self-contained unit. It will be observed that the small motor is insulated from the base-plate, and it should be added that an insulated coupling is provided. The high-vacuum pump is shown mounted direct on the rectifier immediately above the preliminary vacuum pump set. Attention is drawn to the arrangement of piping between the water-cooled anodes and re-cooler.

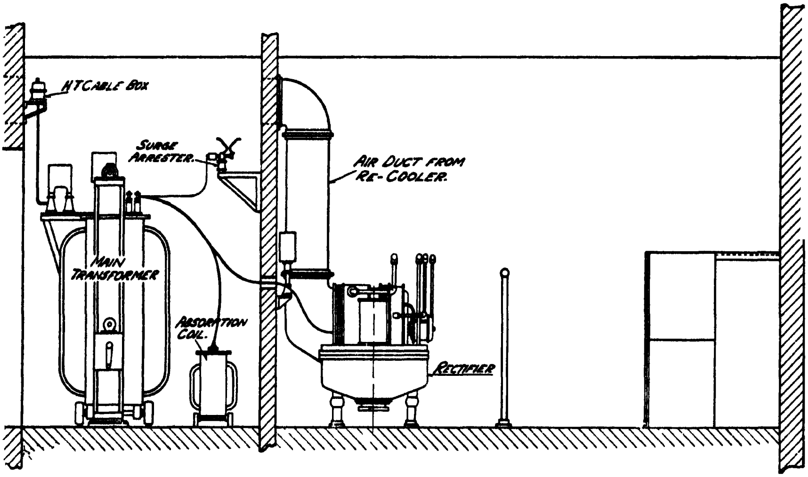

FIG. 241. CROSS-SECTIONAL ELEVATION OF RECTIFIER SUBSTATION
Bruce-Peebles & Co.

The tank is composed of fabricated steel plates of special grade, welded and specially treated to remove all dirt. The vacuum seals are of the mercury type, which enable efficient joints to be made with normal tension of the fixing bolts. There is an advantage in this type of seal in that should any joint develop a leak, the fault is immediately shown by the sinking of the mercury in the indicator gauge, one of which is fitted to each joint. Moreover, while the leak exists, only mercury can gain access to the arc chamber, and this is of small consequence, since it merely adds to the amount of mercury in active use. The twelve anodes are carried by the substantial steel plate forming the top half of the rectifier,

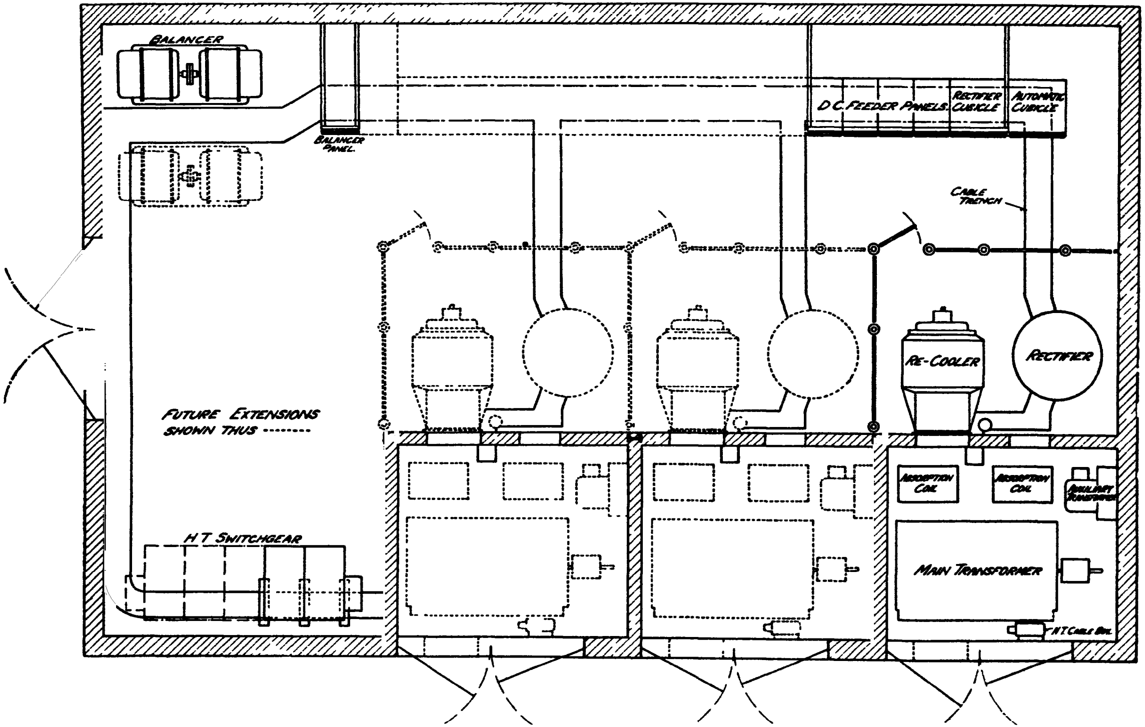

FIG. 242. PLAN VIEW OF RECTIFIER SUBSTATION
Bruce-Peebles & Co.

which can be easily removed to permit of inspection being carried out with a minimum of delay. The complete rectifier stands upon insulators mounted direct on the floor.

Strips of copper, neatly run and securely fixed, form the connections to the anodes, and these are brought out to a terminal board mounted on the outside of the top half of the rectifier in the most suitable position for connecting up to the cables coming from the secondary winding of the transformer. Connection to the cathode or positive terminal is also made by copper strip.

Dealing now with the ignition and excitation circuits, it should be stated that the current for these is supplied by a 7-kVA three-phase 50-cycle 11 000/220-volt oil-immersed transformer: this transformer also supplies current to all the auxiliaries, and it is connected to the incoming feeder by an oil-immersed switch fuse. Two excitation anodes are provided, these being sufficient to maintain the cathode spot. Internal heaters are not fitted, these being unnecessary; and, provided the vacuum is of the correct value, the rectifier may be started up cold and put on load without any delay. It should be mentioned that the high-vacuum pump operates continuously, whether the rectifier is in operation or not.

The rectifier is water-cooled by a Heenan and Froude re-cooler situated adjacent to the rectifier. This takes the form of a motor-operated fan-cooled radiator and motor-driven water-circulating pumps, the complete equipment being mounted on insulators. Two separate cooling systems are provided, one for the rectifier, and the other for the condensation of the mercury in the high-vacuum pump, the same water being used continuously. Fig. 243 shows the recooler equipment and arrangement of piping. The illustration also depicts the substantial screens (three removed for photographing) which completely enclose the plant.

Direct-current distribution is on the three-wire system, and a rotating balancer set is provided capable of dealing with 300 A out-of-balance current. This set, which runs at 500 r.p.m., consists of two protected-type shunt-wound direct-current machines directly connected and mounted on a combination bedplate. It is automatically controlled by means of solenoid-operated circuit-breakers and contactors, and the sequence of operations is such that the balancer is started up immediately the rectifier main circuit-breaker closes. The

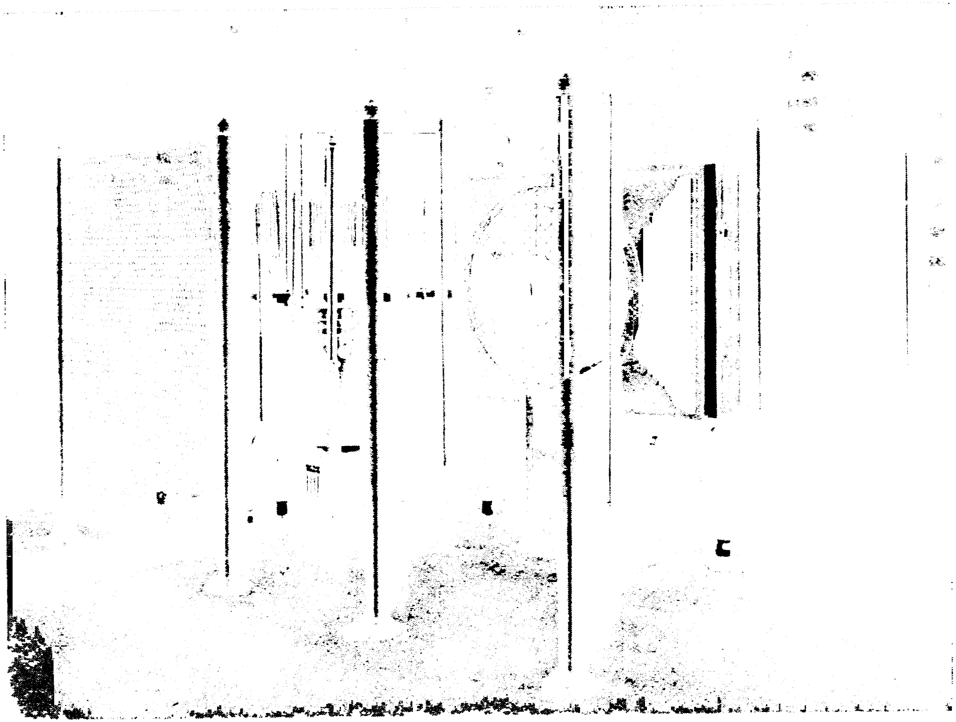

FIG. 243. 1 000-kW RECTIFIER EQUIPMENT WITH RECOOLER
Bruce-Peebles & Co.

main and balancer circuit-breakers are interlocked, so that when the rectifier shuts down the balancer is automatically tripped out.

An oil-immersed transformer operates in conjunction with the rectifier, and is supplied with three-phase 50-cycle current at 11 000 volts. It is provided with motor-operated on-load tap-changing gear to give the necessary voltage variation on the direct-current side. Fig. 244 shows the transformer which, as previously mentioned, is located in a separate cubicle along with the auxiliary transformer and absorption choke coils. The secondary windings are parallel double three-phase connected, and the cables from the twelve phases are carried, through an aperture in the brick wall partition, directly to the rectifier terminal board. The negative pole of the direct-current circuit originates at two absorption choke coils which are connected to the four neutral points of the main transformer secondary winding, an isolating switch being provided at the negative bus-bar. The secondary windings are protected against the possibility of voltage surges by horn-gap arresters.

Rectifier Control. The rectifier is remote-controlled from the main substation situated about a mile distant, and operates in parallel with rotating convertors in that station. In passing, it may be mentioned that the remote control apparatus for the rectifier is similar to that for the rotating convertors, thus giving similarity of control for both types of plant.

The incoming 11 000-volt alternating-current supply is received at a motor-operated oil switch provided with overload protection having instantaneous and inverse time limit characteristics. The automatic control panel, shown in Fig. 245, performs the starting-up and shutting-down operations, and provides for the complete protection of the plant, after the starting impulse referred to below has been given from the control point. This control panel is fitted with a vacuum gauge and main transformer step-switch indicator, and also with switches for changing over the equipment to manual control. The remote-control panel at the control station contains push-buttons for (*a*) start up; (*b*) shut down; (*c*) raise volts; (*d*) lower volts. Remote-control meters give load and voltage conditions. Signals are also provided indicating "plant running"; "shut down"; and "recooler fault."

The starting impulse for the substation is given by depressing

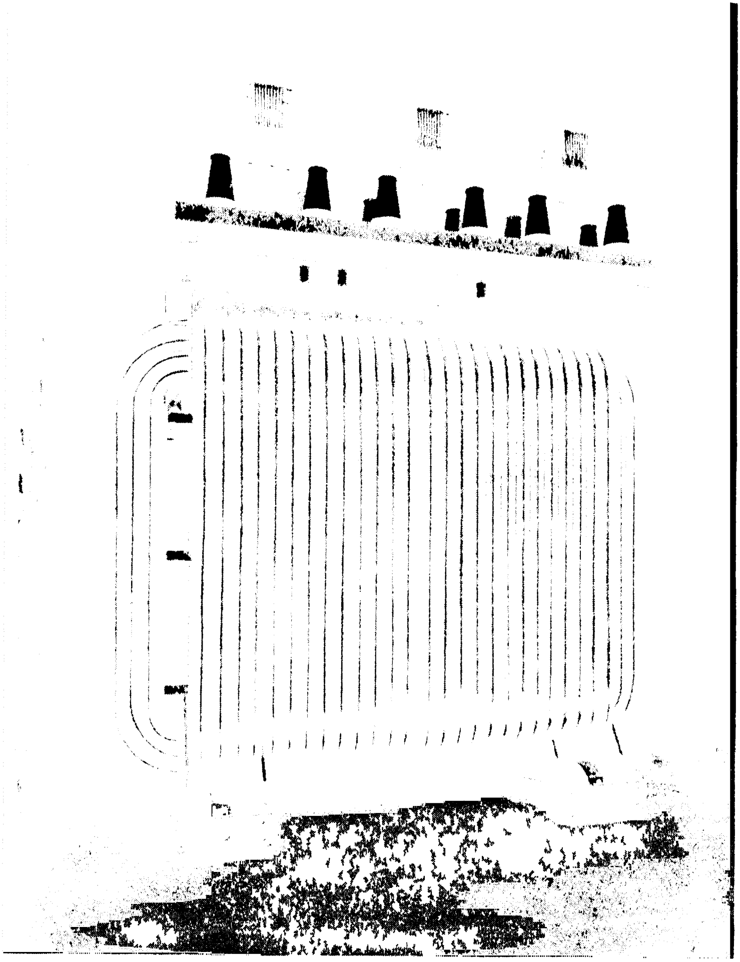

Fig 244 Main Transformer, showing Condenser type Surge Arresters

the "start-up" push-button; this actuates the relays for closing the high-tension oil switch, thereby energizing the main transformer, and at the same time the relay for closing the direct-current circuit-breaker, which is provided with a time lag to ensure that it cannot close before the oil switch. By means of

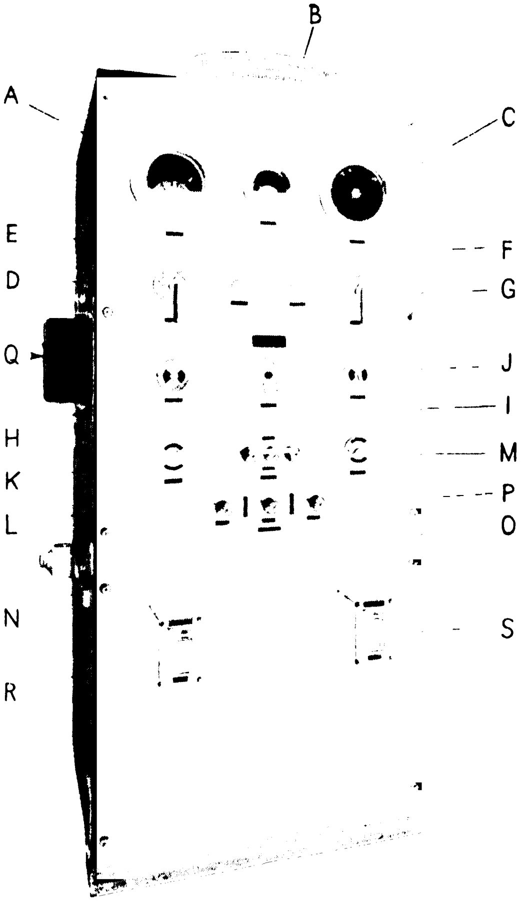

Fig. 245. Automatic Control Panel for Rectifier Equipment

A = Vacuum gauge
B = Excitation ammeter
C = Transformer tap position indicator
D = Alternating-current circuit-control breaker switch
E = Transformer tap switch indicator lamp (green)
F = Transformer tap switch indicator lamp (red)
G = Transformer tap switch
H = Vacuum Pumps "fault" indicator
I = Unlocking switch
J = Lockout switch
K = Control switch for vacuum pumps
L = Pilot wires switch
M = Selective control switch for circuit-breakers
N = Remote control "out" switch
O = Remote control "in" switch
P = Lockout switch
Q = Direct-current circuit-breaker operating relay
R = Transformer tap changing relay (raise volts)
S = Transformer tap changing relay (lower volts)

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auxiliary contacts the ignition and excitation apparatus is energized simultaneously with the closing of the oil switch, thus starting the ignition and excitation automatically. The rectifier is then ready for service and, provided the output voltage is higher than the bus-bar voltage, will pick up load immediately. Remote control of the motor-operated tap-changing gear on the main transformer enables the operator to achieve perfect paralleling. By means of these tappings a voltage variation of 16 per cent can be obtained, and the sixty-six steps provided give a very smooth control range. The high-tension oil switch is interlocked with the step switch, and is immediately tripped out in the event of the step switch remaining in an intermediate position between two tappings.

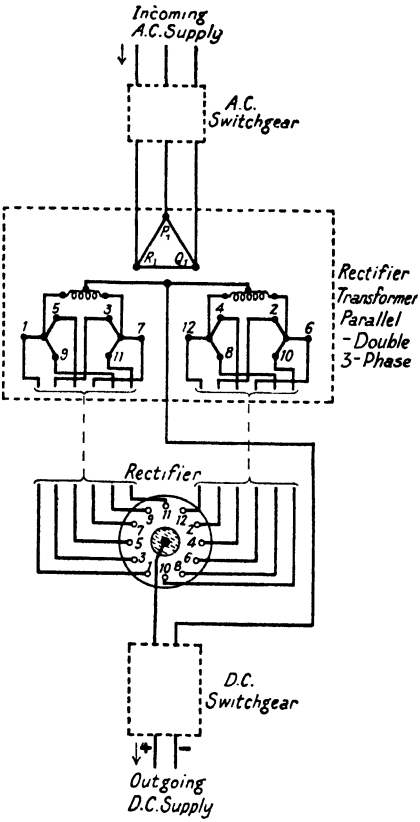

FIG. 246. DIAGRAM SHOWING PRINCIPAL CONNECTIONS OF RECTIFIER EQUIPMENT

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Correct vacuum is automatically maintained by contacts on the vacuum gauge, the needle of which controls the starting up and shutting down of the preliminary vacuum pump. This needle will also cause a "lock out" of the rectifier should the vacuum be too low for satisfactory operation. In the event of the temperature of the rectifier exceeding a predetermined limit, it is shut down by means of a contact thermometer mounted on the anode plate. Should the oil switch and main circuit-breaker be tripped due to any cause, a second attempt is made to close, and if this fails the plant is shut down, the appropriate signal being then given at the main substation. Failure of the recooler fan or pump motors is also signalled to the main substation, while simultaneously causing the relay for the vacuum pumps to open the heating-plate circuit of the high-vacuum pump. Immediately the fault is removed the heating-plate circuit is again made.

The direct-current feeder panels are situated adjacent to the rectifier circuit-breaker and automatic panels, the feeders being connected to the bus-bars by double-pole hand-operated circuit-breakers with overload features and isolating switches. The feeders are normally closed on the bus-bars.

It is interesting to note, in conclusion, that such a system of remote control seems to be the accepted practice for lighting and power systems; whereas on tramway systems the practice is to switch the rectifier into service when the substation bus-bar voltage falls to a predetermined value (i.e. as the load on the system increases), the rectifier being switched out of service when the current loading drops to a predetermined value.

The diagram of Fig. 246 shows the principal connections of the complete rectifier installation.

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